Technical Report CERC-95-3
March 1995

US Army Corps of Engineers
Waterways Experiment Station

Periodic Inspection of Cleveland Harbor East Breakwater, Ohio

Report 1
Base Conditions

by *Robert R. Bottin, Jr., WES*

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U.S. Army Engineer District, Buffalo

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Prepared for Headquarters, U.S. Army Corps of Engineers

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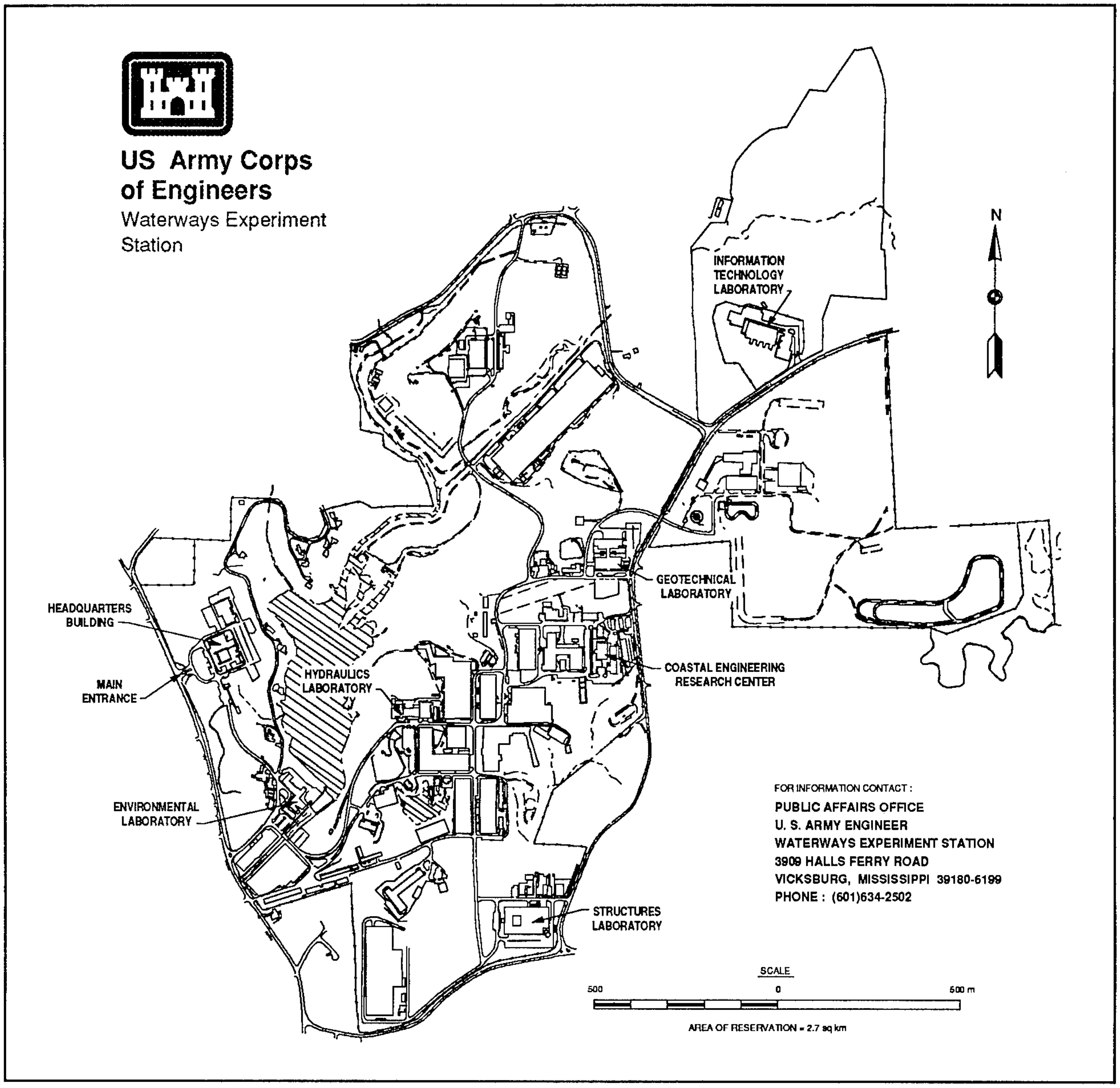

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Contents

Preface

The study reported herein was conducted as part of the Monitoring Completed Coastal Projects (MCCP) program. Work was carried out under Work Unit 22121, "Periodic Inspections." Overall program management for MCCP is accomplished by the Hydraulic Design Section of Headquarters, U.S. Army Corps of Engineers (HQUSACE). The Coastal Engineering Research Center (CERC), U.S. Army Engineer Waterways Experiment Station (WES), is responsible for technical and data management and support for HQUSACE review and technology transfer. Technical Monitors for the MCCP program are Messrs. John H. Lockhart, Jr., John G. Housley, and Barry W. Holiday (HQUSACE). The Program Manager is Ms. Carolyn M. Holmes (CERC).

This report is the first in a series which will track the long-term structural response of the Cleveland Harbor East Breakwater, Ohio, to its environment. The information contained in this report was gathered as a result of land and aerial survey work conducted by Richard B. Davis Company, Inc., under contract to the Corps of Engineers, and a broken armor unit survey conducted by Messrs. Michael C. Mohr, David W. Marcus, and Shanon Chader, U.S. Army Engineer District, Buffalo, (CENCB) and Messrs. Robert R. Bottin, Jr., Gordon S. Harkins, Larry R. Tolliver, Etienne Trahan, Jr., and John E. Evans (CERC).

The work was conducted during the period July-November 1993 under the general supervision of Dr. James R. Houston and Mr. Charles C. Calhoun, Jr., Director and Assistant Director, CERC, and under direct supervision of Messrs. C. E. Chatham, Jr., Chief, Wave Dynamics Division, and Dennis G. Markle, Chief, Wave Processes Branch. This report was prepared by Messrs. Bottin, Marcus, and Mohr.

Director of WES during the investigation and publication of this report was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI (Metric) Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	2.54	centimeters
miles (U.S. statute)	1.609347	kilometers
pounds (mass)	0.4535924	kilograms
tons (2,000 pounds, mass)	907.1847	kilograms

1 Introduction

Work Unit Objective and Monitoring Approach

The objective of the Periodic Inspections work unit in the Monitoring Completed Coastal Projects (MCCP) research program is to periodically monitor selected coastal structures to gain an understanding of the long-term structural response of unique structures to their environment. These periodic data sets are used to improve knowledge in design, construction, and maintenance of both existing and proposed future coastal projects. These data will also avoid repeating past design deficiencies which have resulted in structure failure and/ or high maintenance costs. Past projects monitored under the MCCP program, and/or structures with unique design features that may have application at other sites, are considered for inclusion in the periodic inspections monitoring program. Selected sites are presented as candidates for development of a periodic monitoring plan. Those sites receiving favorable response during MCCP program review are inspected and a monitoring plan is developed and presented for approval. Once the monitoring plan for a site is approved by the field review group and funds are provided, monitoring of the site is initiated. Normally, base conditions are established and documented in the initial effort. The site then is reinspected on a periodic basis (frequency of surveys are based on a balance of need and funding for each monitoring site) to obtain long-term structural performance data.

Relatively low-cost remote sensing tools and techniques, with limited ground truthing surveys, are the primary inspection tools used in the monitoring efforts. Most periodic inspections consist of capturing above-water conditions of the structure at periodic intervals using high resolution aerial photography. A visual comparison of periodic aerial photos is used to gage the degree of in-depth analysis required to quantify structural changes (primarily armor unit movement). Data analysis involves using photogrammetric techniques developed for and successfully applied at other coastal sites. At sites where local wave data is being gathered by other projects or agencies and acquisition of these data can be made at a relatively low cost, wave data are correlated with structural changes. In areas where these data are not available, general observations and/or documentation of major storms occurring in the locality are presented along with the monitoring data. Ground surveys are limited to the level needed to establish the accuracy of the photogrammetric techniques.

When a coastal structure is photographed at low tide, or low lake levels, an accurate permanent record of all visible armor units is obtained. Through the use of stereoscopic, photogrammetric instruments in conjunction with photos, details of structural geometry can be defined at a point in time. By direct comparison of photos taken at different times, as well as the photogrammetric data resolved from each set of photos, geometric changes (i.e., armor unit movement and/or breakage) of the structure can be defined as a function of time. Thus, periodic inspections of the structures will capture permanent data that can be compared and analyzed to determine if structure changes are occurring that indicate possible failure modes and the need to monitor the structure(s) more closely. Portions of the Cleveland Harbor East Breakwater were nominated for periodic monitoring by the U.S. Army Engineer District, Buffalo (CENCB).

Project Location and Brief History

Cleveland Harbor is located on the southern shore of Lake Erie, 154 km (96 miles)[1] east of Toledo, Ohio, and 283 km (176 miles) west of Buffalo, New York (Figure 1). The harbor is situated at the mouth of the Cuyahoga River. It comprises approximately 5.3 sq km (1,300 acres) and extends for a distance of about 7,620 m (25,000 ft) parallel to the shore (U.S. Army Engineer District, Buffalo 1976). Cleveland Harbor is protected by a breakwater system, which is over 9,144 m (30,000 ft) in aggregate length. There are two harbor entrances connecting the harbor with Lake Erie. The west entrance is directly lakeward of the Cuyahoga River mouth and the east entrance is at the eastern end of the east breakwater. Shallow-draft and recreational vessels can enter the harbor through a narrow opening in the west breakwater, which connects to Edgewater Marina (located adjacent to the west end of Cleveland Harbor). Aerial photos showing the layout of Cleveland Harbor are presented in Figures 2 and 3.

Cleveland Harbor accommodates the waterborne movement of bulk and general cargo to and from the city of Cleveland, the largest city in Ohio, and one of the major commerce ports in the Great Lakes system. The harbor also serves several developments within Cleveland and throughout industrial and commercial portions of the state of Ohio and adjacent states. Vessel movements of bulk iron ore, stone, sand and gravel, and salt represent over 90 percent of the waterborne commerce. Forecasts indicate that these commodity

[1] Units of measurement in the text of this report are shown in SI (metric) units, followed by non-SI (British) units in parenthesis. Units of measurement on figures are shown in British units, however, a table of factors for converting non-SI units of measurement to SI units is presented on page v.

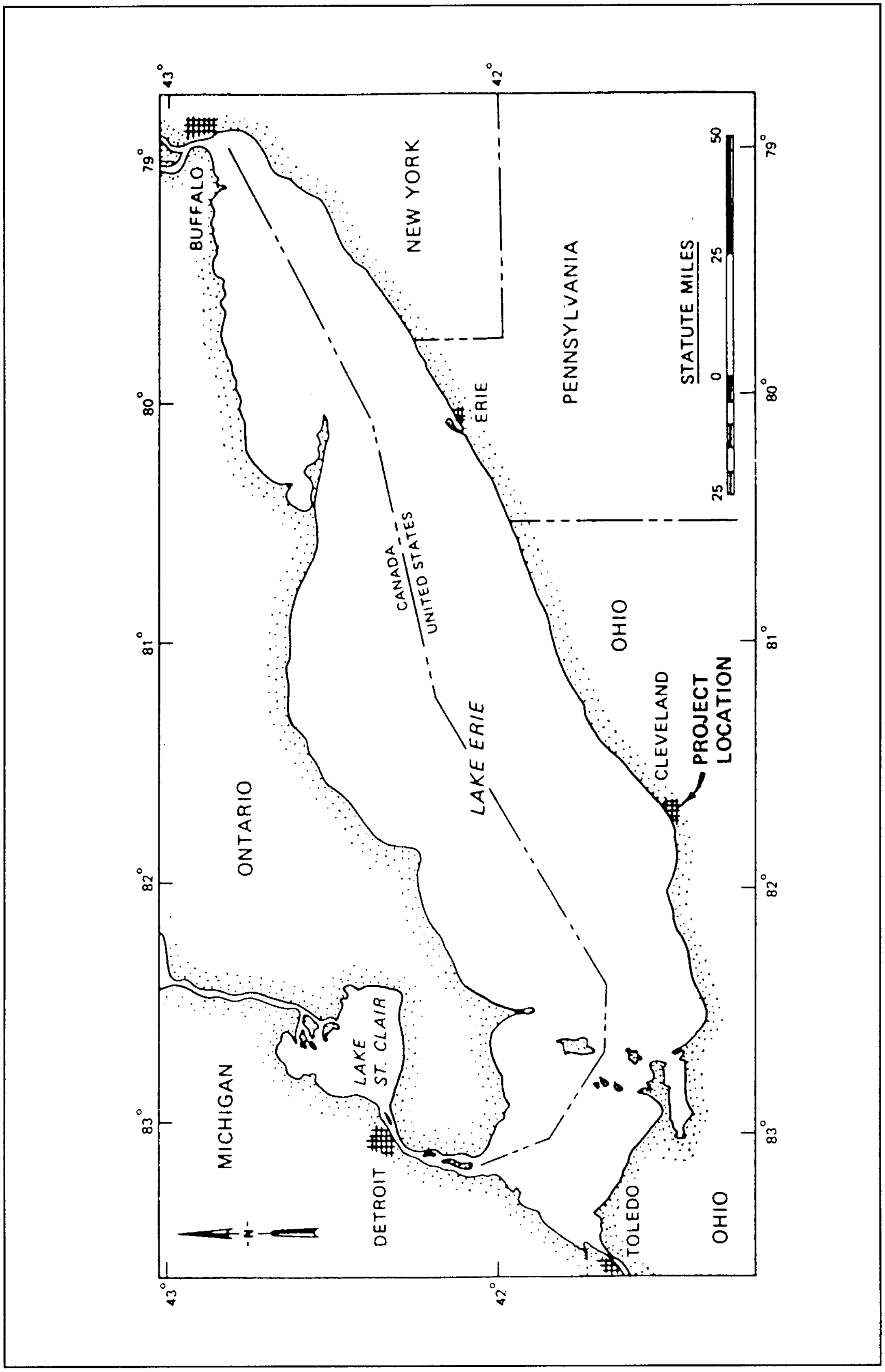


Figure 1. Project location

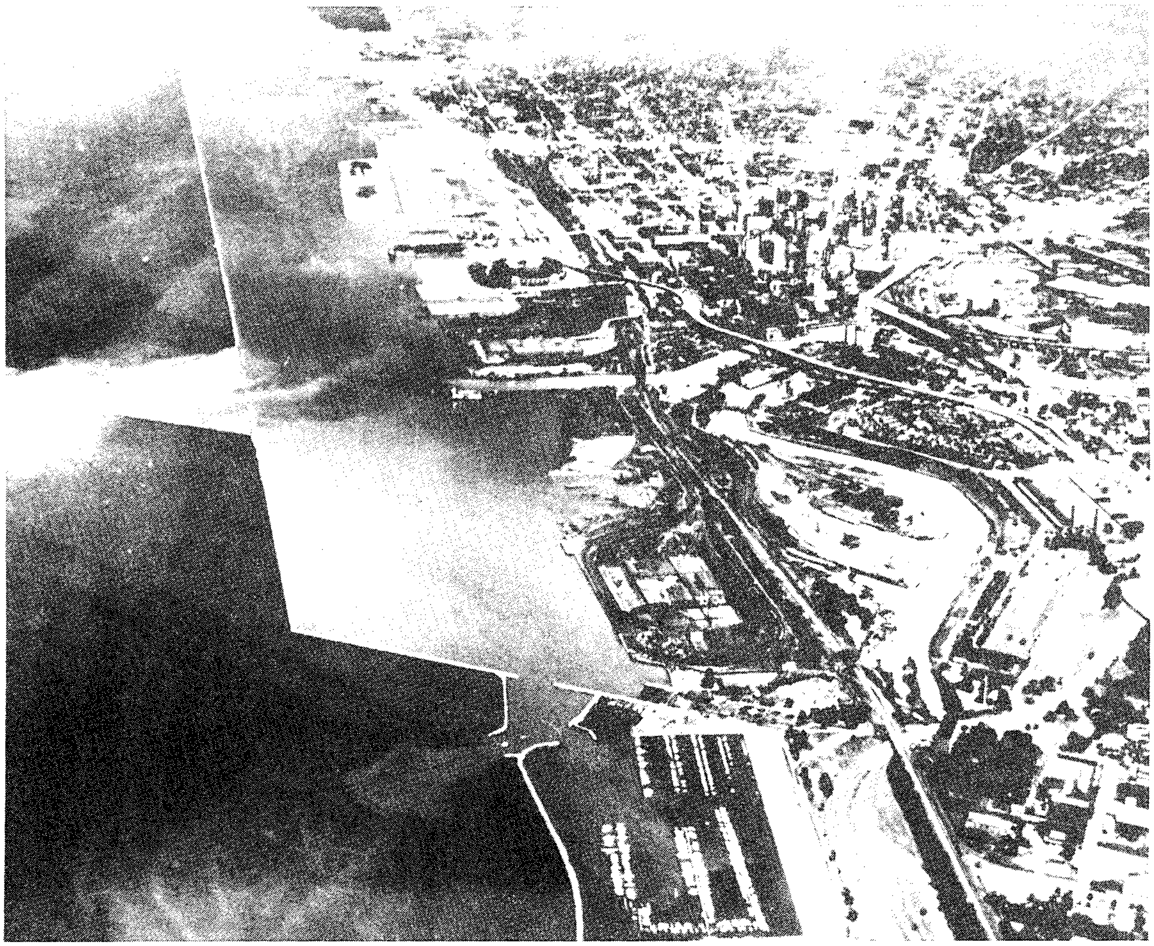


Figure 2. Aerial photo of Cleveland Harbor (looking east)

movements will increase in the future and will continue to be the dominant portion of waterborne commerce at Cleveland.

The Cleveland Harbor breakwater provides protection to commercial shipping and allows vessels to maneuver and serve industry in the Cleveland Outer Harbor during stormy weather. The structural stability of the shoreline in the lee of the structures, which includes mooring areas, commercial developments, and an airport, is dependent upon the breakwater's ability to reduce the severity of storm induced wave action. The breakwater also provides a harbor of refuge and boating area for small pleasure craft during storm wave conditions. The large sheltered harbor basins are popular recreation boating areas that frequently host a range of waterborne activities.

The length of the existing east breakwater is 6,392 m (20,970 ft). The westerly 914-m-long (3,000-ft-long) portion was constructed between 1887 and 1900, and was composed of a stone-filled timber crib structure with a concrete cap. During the period 1917-1926, a stone superstructure, including a sloping stone armoring, was placed on the lakeward side (Figure 4). The easterly 5,477 m (17,970 ft) portion was constructed between 1903 and 1915 and

Figure 3. Aerial photo of Cleveland Harbor (looking west)

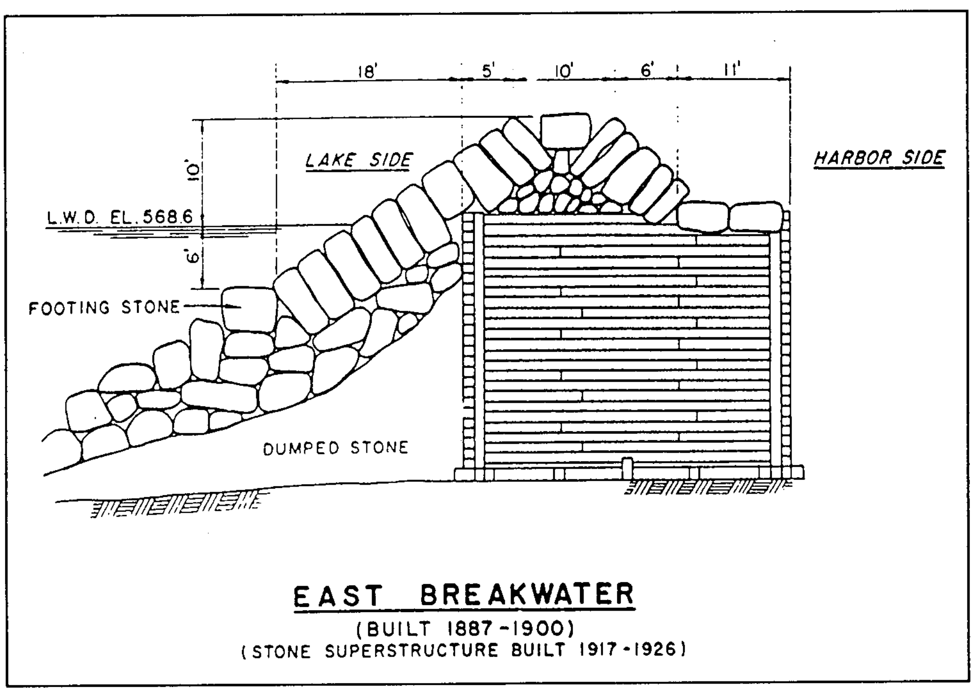


Figure 4. Cross section of western 3,000-ft portion of Cleveland Harbor east breakwater

consisted of dumped core stone covered with large individually placed armor stone (Figure 5). The breakwater has a design crest elevation (el)[1] of 3.14 m (+10.3 ft) and a crest width of 3.05 m (10 ft). The side slopes were constructed with 1V:1.5H slopes. A U.S. Coast Guard lighthouse is located at the easterly end of the breakwater at its head. It was constructed on a 6.4- by 6.4 m (21- by 21-ft) square concrete footing. Depths on the lake side of the structure range between -9.1 and -10.7 m (-30 and -35 ft). Depths are more shallow on the harbor side due to natural accretion of sediments within the harbor since construction.

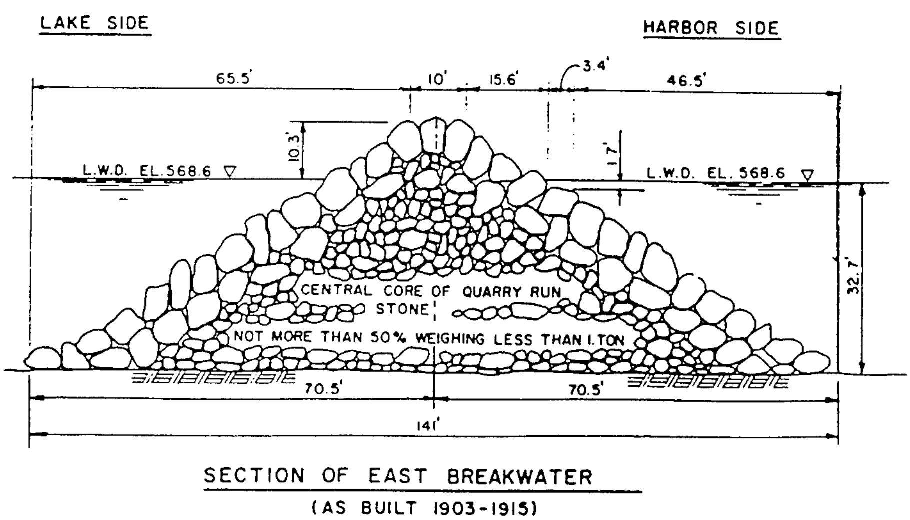


Figure 5. Cross section of eastern 20,070-ft portion of Cleveland Harbor east breakwater as originally constructed

The east breakwater has had an extensive repair history (Bottin 1988). Storm damage has caused the displacement of laid-up cover stone, especially on the lake side, resulting in the continuous unravelling of the breakwater slope in many areas. Some deterioration and loss of individual cover stone had also resulted in exposure of the underlayer core stone. Subsequent loss of core stone during storm conditions has resulted in futher deterioration of the structure and some sections have collapsed. The structure's integrity has been adversely affected in the zone from -3.05 m to +3.14 m (-10 ft to +10.3 ft). Most of the structure damage was on the lake side with eventual deformation

[1] Elevations cited in Chapters 1 and 2 of this report are in meters (feet) referred to low-water datum (LWD), el 173.3 m (568.6 ft) above mean water level at Father Point, Quebec (International Great Lakes Datum (IGLD), 1955). In 1985, IGLD was redefined at el 173.5 m (569.2 ft).

to the harbor side of the breakwater in areas where timely repairs were not made.

Repairs to the structure, historically, were made by rebuilding the damaged portion above 3.05 m (10 ft) in a manner similar to the original construction using 2,722- to 7,257-kg (3- to 8-ton) stone. Below -3.05 m (-10 ft), additional stone weighing between 9,072 and 12,700 kg (10 and 14 tons) was randomly placed on the existing cover stone to help provide a base for the upper slope. Repairs were made to the east breakwater in 1927, 1928, 1930, 1932-1934, and 1946-1978. During the period 1965-1978, maintenance on the breakwater involved repairs to about 2,438 lin m (8,000 lin ft) at an expenditure in excess of $8,000,000.

A major rehabilitation project involving the easterly 1,341 m (4,400 ft) of the east breakwater was completed in 1979 (Figure 6). It involved repairing the structure with dolos concrete armor units. The lakeward slope, and in some areas the crest, were rebuilt using 1,814 kg (2-ton) dolos placed on a 1V:2H slope on the breakwater trunk. A typical section of the rehabilitated breakwater trunk is shown in Figure 7. The east head involved a section similar to the trunk but the slope was constructed on a 1V:2.5H to maintain stability. More information on the design of the dolos rehabilitation can be obtained from U.S. Army Engineer District, Buffalo (1979). The rehabilitated dolos section was monitored under the MCCP program and is discussed in Chapter 2. Additional dolosse were placed on the head section in 1982 and 1987 to repair storm damages.

During the period 1985-1986 and 1988-1989 approximately 1,890 m (6,200 ft) of the lakeward face of the east breakwater was rehabilitated with 8,165 to 18,144 kg (9 to 20 ton) stone on a 1V:1.5H side slope. This rehabilitation design was optimized through model tests conducted at CEWES (Markle and Dubose 1985). In 1992, a cumulative length of 549 m (1,800 ft) of the east breakwater was rehabilitated with 3,900 to 8,700-kg (4.3 to 9.6-ton) stone installed on a 1V:2H slope on the structure's lakeward side. Limited monitoring of various reaches of these rehabilitations have been conducted and are detailed in Chapter 2 of this report.

Purpose of the Study

The purposes of the study reported herein were to:

a. Develop methods using limited land based surveying, aerial photography, and photogrammetric analysis to assess the long-term response of dolos and selected stone armor unit sections on the Cleveland Harbor East Breakwater.

b. Conduct land surveys, broken armor unit inspections, aerial photography, and photographic analysis to:

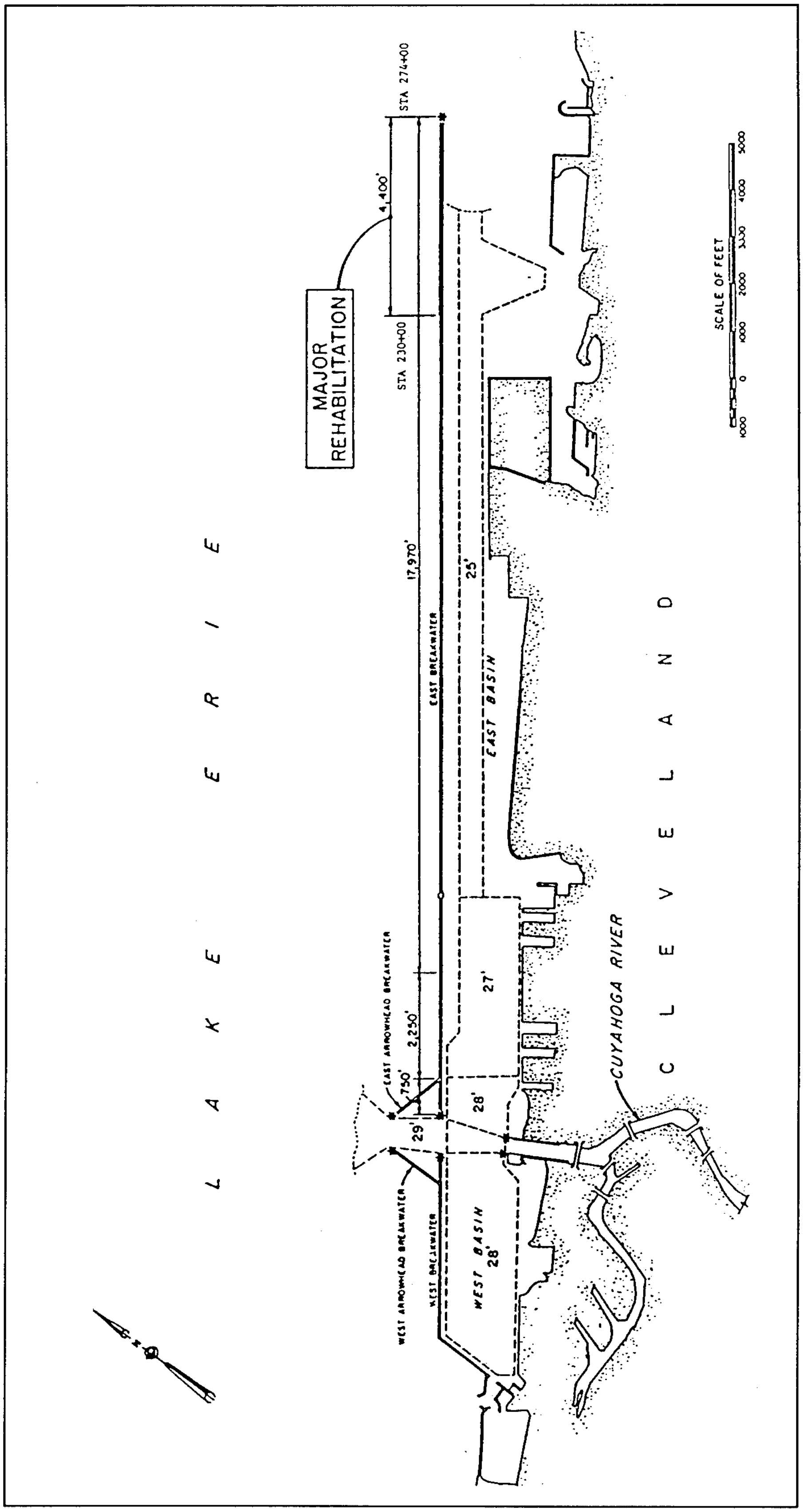


Figure 6. Major rehabilitation of east breakwater completed in 1979

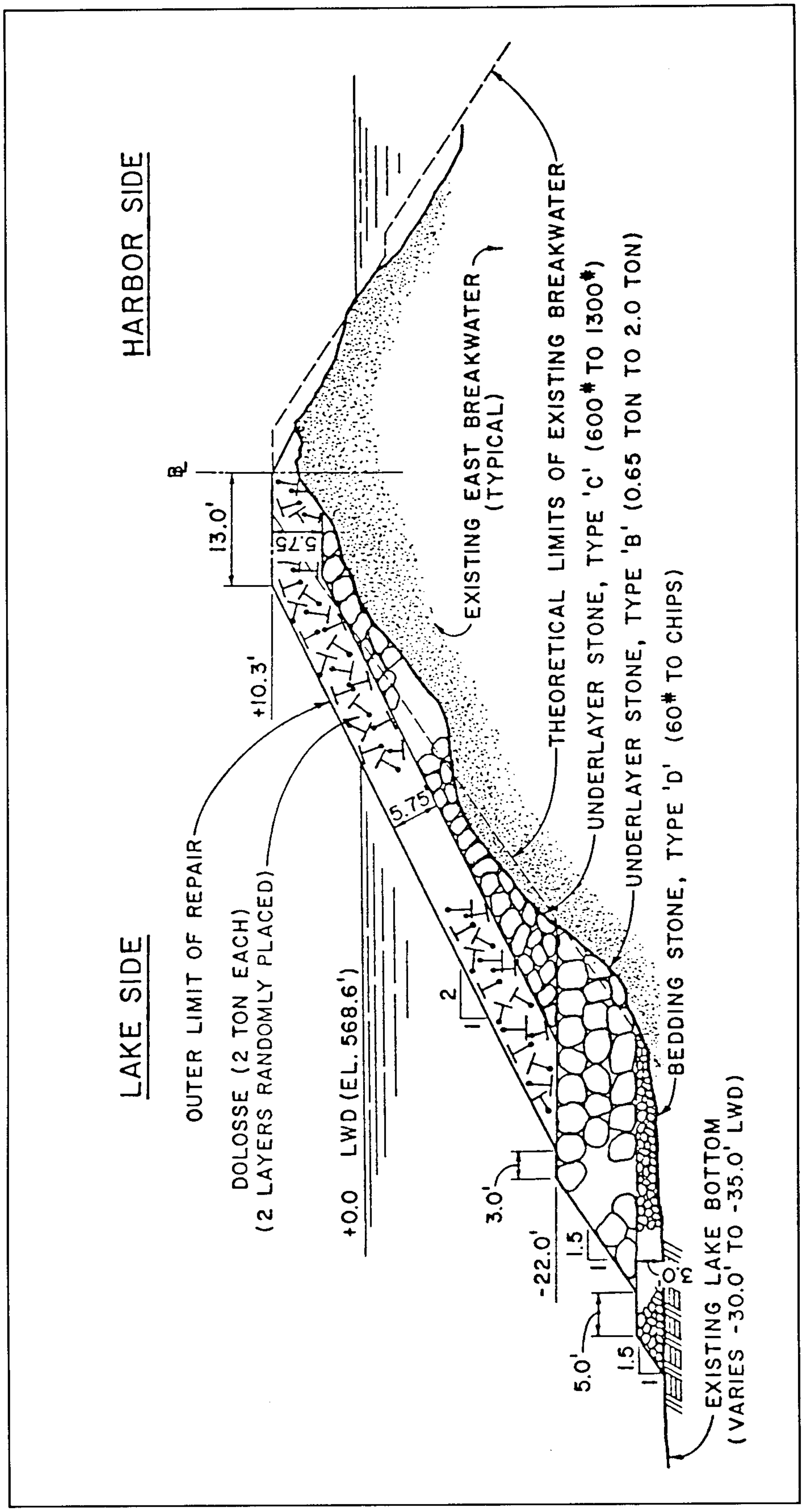


Figure 7. Cross section of rehabilitated breakwater trunk

(1) Test and improve developed methodologies to accurately define armor unit movement above the waterline.

(2) Establish base conditions for the breakwater's armor units which can be used as controls when the structure is revisited in the future under the Periodic Inspections work unit.

c. Reexamine data obtained in previous monitoring efforts and determine if changes relative to the armor layer have occurred.

2 Prior Monitoring of the Site

Dolos Armor Unit Monitoring

General

The 1979 dolos breakwater rehabilitation project at Cleveland Harbor was selected for monitoring under the Monitoring Completed Coastal Projects (MCCP) program in 1980 as the program's first project during its first year of authorization (Pope, Bottin and Rowen 1993). The primary objective of the Cleveland Harbor East Breakwater rehabilitation monitoring plan was to determine the stability of a dolos armor unit cover. This was the first time dolosse were used by the United States on an offshore structure in the Great Lakes environment. Views of the dolos-rehabilitated trunk and head are presented in Figures 8 and 9. The monitoring program was also to evaluate the magnitude of armor unit breakage which could compromise the integrity of the structure.

The monitoring program at Cleveland was originally scheduled to cover the period November 1980-September 1983; however, a severe, near design lake storm was experienced at Cleveland on 6 April 1982. The storm resulted in observable movement and breakage of dolosse along the breakwater trunk. Many dolosse above the waterline were also removed from the north side of the breakwater head. The damaged head section was repaired in October 1982, and, as a result of the storm and subsequent repair, a reduced monitoring program continued for an additional two years, until September 1985.

The monitoring program incorporated the use of several observational, direct measure, and remote sensing methodologies. It included the collection of aerial photography, wave and water level data, survey data to determine armor unit movement above the waterline, an inventory of broken dolos units, time lapse photography, and underwater surveys utilizing both side-scan sonar and diver inspections. Results of the study were published in Pope, Bottin, and Rowen (1993). Aerial photography, armor unit movement data, and broken armor unit survey data, which are relative to the Periodic Inspections work unit, are summarized below.

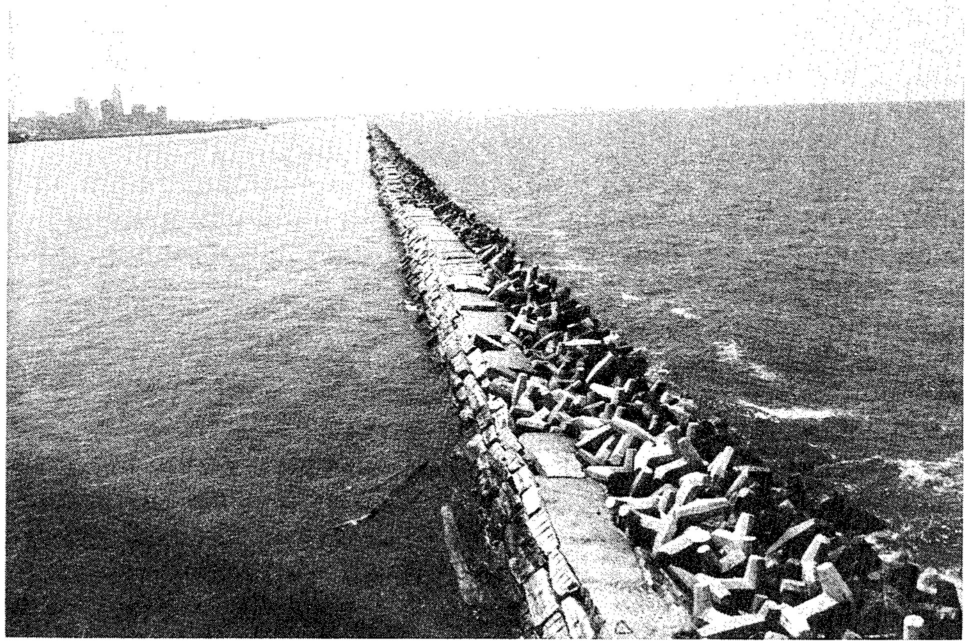


Figure 8. View of dolos-rehabilitated east breakwater trunk (dolosse installed on lakeside of structure)

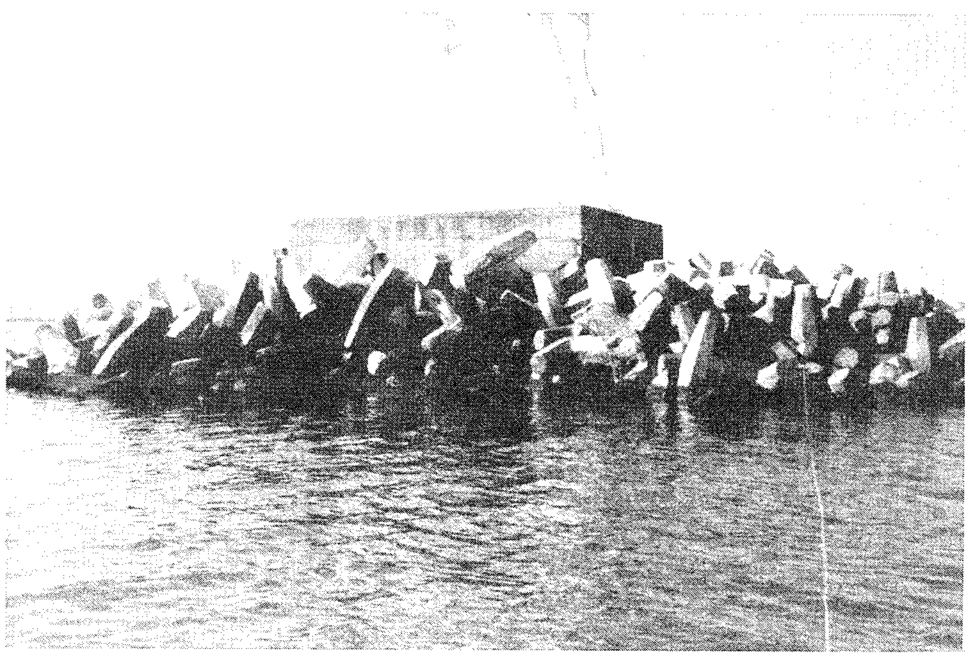


Figure 9. View of dolos-rehabilitated east breakwater head

Aerial photography

Ten reference stations (Figure 10) were established along the crest of the rehabilitated east breakwater, and targets were painted and surveyed for aerial

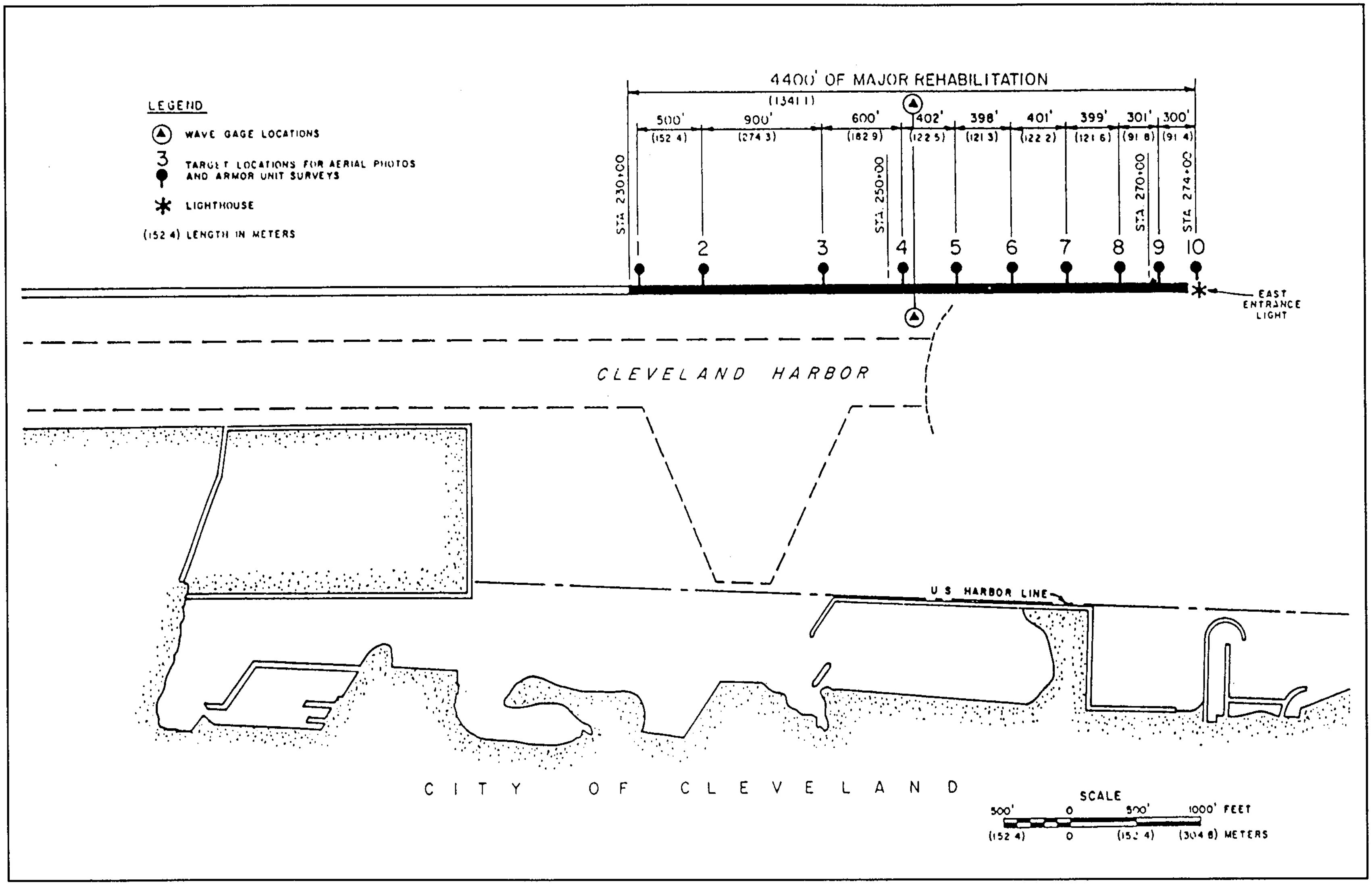


Figure 10. Reference stations established along rehabilitated east breakwater

photography control. Aerial photos were obtained on 11 occasions during the monitoring effort. They were enlarged and used in evaluating both zone and unit changes in the dolos armor cover during the monitoring period, however, there were some drawbacks. The images were not completely rectified and the enlarged scales varied across the images. Direct comparisons on a light table required continuous shifting of the images. An observable parallax effect distorted the apparent positions of the dolosse on each enlargement. Thus, the photos could not be used to quantify armor unit movement.

Armor unit movement data

Selected dolosse were targeted, painted, and surveyed periodically to document individual unit movement during the monitoring period. Two dolosse, one near the waterline and one near the crest, were selected and co-located with the aerial photography targets. This resulted in 20 painted dolosse on the trunk. In addition, 12 dolosse around the east breakwater head were painted and surveyed periodically. The April 1982 storm resulted in armor movement along the breakwater trunk and removal of most dolosse above LWD over a 6.1-m-wide (20-ft-wide) section on the breakwater head. About 65 units were "popped" away from the impermeable, vertical-faced concrete lighthouse base and strewn downslope as broken fragments. As a result of the storm, 200 additional dolosse were placed on the head section in October 1982 to repair the damage zone and widen the head's crest (from a two-dolos to a three-dolos width). New target dolosse were identified and monitored. Target dolos density and the number of inspections for the head section increased. Twenty-one new dolosse were designated for survey following the April 1982 storm. During the October repair, displaced dolosse along the trunk sections were also repositioned and additional units placed as necessary.

Of the 20 target dolosse established initially along the breakwater trunk, data were collected for 12 units over the entire monitoring program. The other eight units were either lost, broken, or inaccessible. Three of these missing armor units were replaced by newly targeted dolosse. Dolosse at the crest of the breakwater proved to be considerably more stable than those at the waterline. Of the 10 targeted dolosse at the waterline, four were missing, two were broken, and one was inaccessible at the end of the monitoring program. The remaining three settled into the structure. One of the crest dolos was lost, and the others settled into the structure. On the head section of the breakwater, only four of the 12 target dolosse remained intact throughout the monitoring period. As with the trunk section, the head section dolosse near the waterline moved more than those at the crest. The waterline target dolosse in the head section area, which is exposed to direct wave action, moved considerably. Even the dolosse on the sheltered harbor side of the head moved.

The majority of armor unit movement during the study was characterized by settlement or rotation into the structure. Settlement is when a dolos loses elevation uniformly, and rotation involves one end of the dolos rising while the other end loses elevation. The dolos cover was considered dynamic throughout the monitoring period and stabilization was never realized.

Broken armor unit survey data

Above-the-water inventories of broken dolosse were conducted 10 times during the monitoring period. Each dolos was uniquely identified by a casting date and serial number branded into one end of a fluke during original casting. During each inspection, the number, date of casting, location relative to the baseline, and type of break were recorded in tabular form for each broken dolos above the waterline. Breaks from all surveys were categorized according to production date, offset from baseline, distribution of breaks along the breakwater, and type of breaks. Breaks were categorized as occurring in the stem or the fluke and if the break was straight across or at some angle to the dolos limb. The stem, or shank, is the central beam of a dolos, and the fluke are the beams on the ends of the armor unit.

Evaluation of the broken dolos survey results from April 1980 to September 1985 indicated a total of 692 broken units above the waterline. The rate of new breakage appeared to have decreased slightly with time as shown by the cumulative number of broken units during the monitoring period (Figure 11). Approximately 30 percent of the dolosse were placed above the average annual mean lake level during construction. Therefore, about 8,972 dolosse of the total 29,741 were placed above the waterline within the primary wave impact zone. With 692 units broken, this yielded approximately an 8-percent breakage rate over the monitoring period ignoring below-water breakage.

Considering the types of breaks, the majority were fluke breaks, and the number of angled breaks exceeded the number of straight breaks. The majority of stem breaks exhibited no dominance of either angled or straight breaks. Comparison of breakage to production data showed that no production group had an unusual amount of breakage. The average breakage per month of production was about 2 percent. Evaluation of the data with regard to offset from the baseline along the crest indicates that the majority of breakage occurred near the waterline.

In general, the rate of breakage fluctuated over the monitoring period, though new breaks appeared to be decreasing during the last survey. Over one-third of the breakage occurred during the first year. Almost 60 percent of the breakage occurred between June 1980 and April 1981 and November 1981 and May 1982, which covers the first year following construction and the period surrounding the April 1982 storm. Changes in the breakage rate can be accounted for partially by settling of the dolos cover. Also, differences in the water level will change the number of units visible during a survey, thereby influencing the broken dolos count during periods of high or low water. Reasons for dolos breakage may include (a) stress patterns within the original cast dolosse, (b) handling and placement, (c) settling of the structure, stressing units within the breakwater, (d) wave-induced displacement, (e) wave-induced

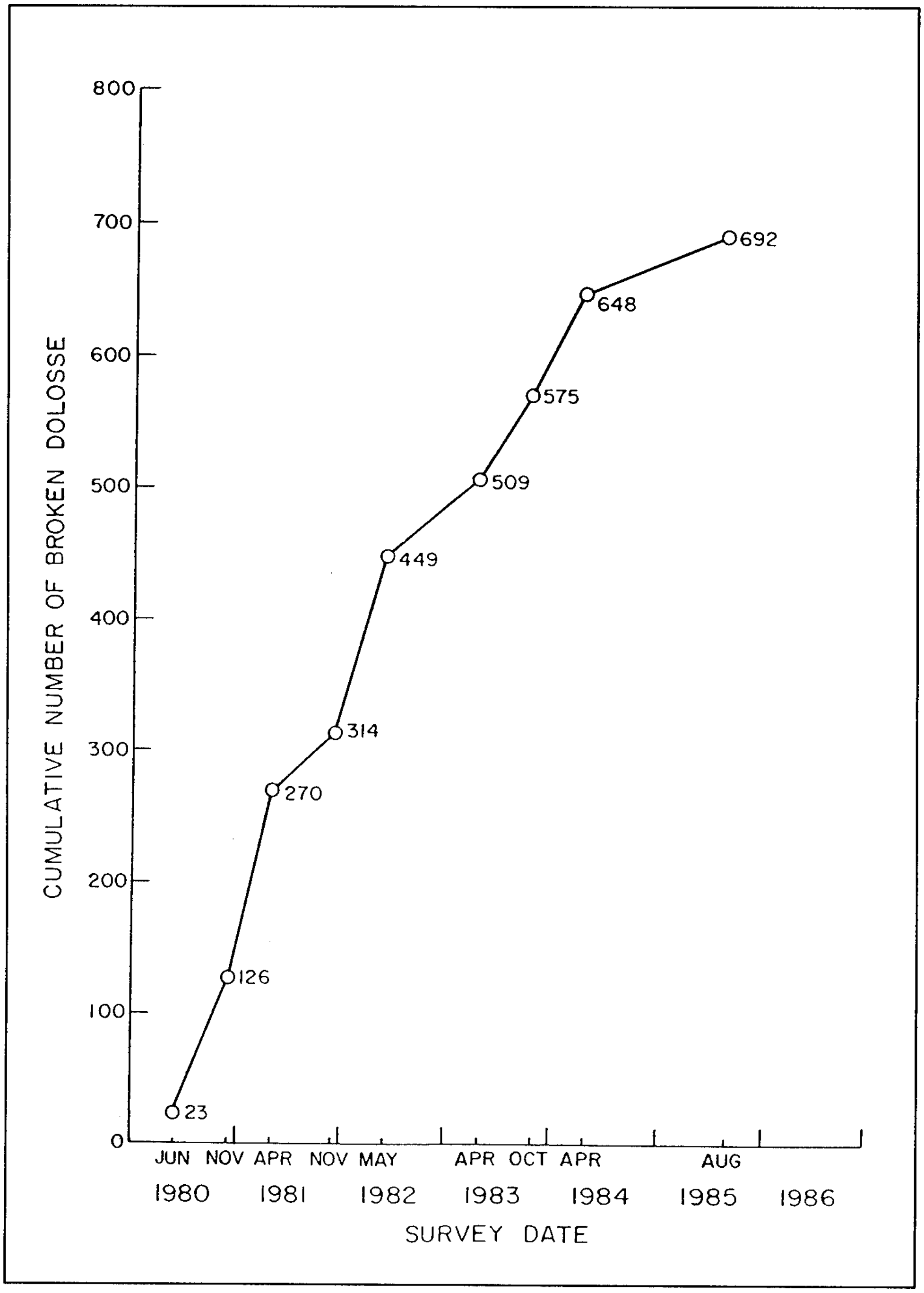


Figure 11. Cumulative number of broken dolos during the monitoring period

rocking and fatigue failure, (f) ice pressure and movement, and (g) impact from debris and dolos fragments.

Conclusions from previous dolos monitoring

Overall conclusions, drawn relative to the prior monitoring effort for the Cleveland Harbor east breakwater (Pope, Bottin and Rowen 1993) were as follows:

a. Although the 1,814-kg (2-ton) dolos armor layer has deteriorated over the years, the breakwater continues to provide the required level of shore protection. Maintenance of the dolos cover has been on an as-needed basis. Repairs, including repositioning and/or the installation of additional armor units, are required after major storms.

b. Wave reflection off the vertical concrete navigation light foundation at the breakwater head appears to contribute to the loss of armor units in that area. Dolos armor units are very porous when a two-layer thickness is used. Wave energy transmits through the dolosse at Cleveland and reflects back upon them, apparently popping them out of place. Additional layers over reflective surfaces may be prudent for highly porous armor units.

c. As evidenced by significant movement and breakage, the 1,814-kg (2-ton) dolosse appear to be underdesigned for the Cleveland East Breakwater. A two-dimensional model study (Markle and Dubose 1985) also indicated that 3,628-kg (4-ton) armor units (as opposed to 1,814 kg (2 ton)) would decrease the probability of movement.

d. During the monitoring period, the 1,814-kg (2-ton) dolos cover continued to subside and lose elevation. Breakage of armor units also occurred throughout the monitoring period, but the rate of breakage appeared to decrease slightly toward the end of the study. Most breakage occurred along the waterline in the active wave zone. Little continued breakage was noted below the waterline during diving inspection.

e. Aerial photography of the dolos cover proved to be a useful tool during the monitoring program in spite of the fact that the photos were not completely rectified. Photos were used to evaluate qualitative changes in the armor cover. This photography served as the basis for planning maintenance and repair of damage zones during the monitoring period.

f. Wave gages were not deployed at Cleveland during the winter months because of concern that they would be lost to ice. Unfortunately, most severe storms during the monitoring period occurred during the winter. The wave data collected, therefore, were not representative of the most severe storm conditions.

g. Side-scan sonar surveys proved to be a valuable means for obtaining qualitative documentation of the condition of the structure toe and the consistency of the cover layer slope. Combined with diving surveys, the underwater condition of the dolos was determined to have several flaws from original construction, including zones of no armor and areas where the toe appears unstable.

Postmonitoring rehabilitation

The winter of 1986-1987, subsequent to the conclusion of the monitoring program, was characterized by higher than average lake levels, and several storms occurred during the period. In the spring of 1987, it was noted that most of the 1,814-kg (2-ton) dolosse around the head of the lighthouse on the eastern end of the structure were missing (Figure 12). The damage was evaluated and in May 1987, 234 dolos armor units were placed around the head (Figure 13). These were 3,628-kg (4-ton) units as opposed to the 1,814-kg (2-ton) units previously used. Several 3,628-kg (4-ton) dolosse were also placed in low areas along the trunk to bring it back to the correct elevation. The 3,628-kg (4-ton) units appear to have remained stable around the head of the east breakwater since the 1987 rehabilitation.

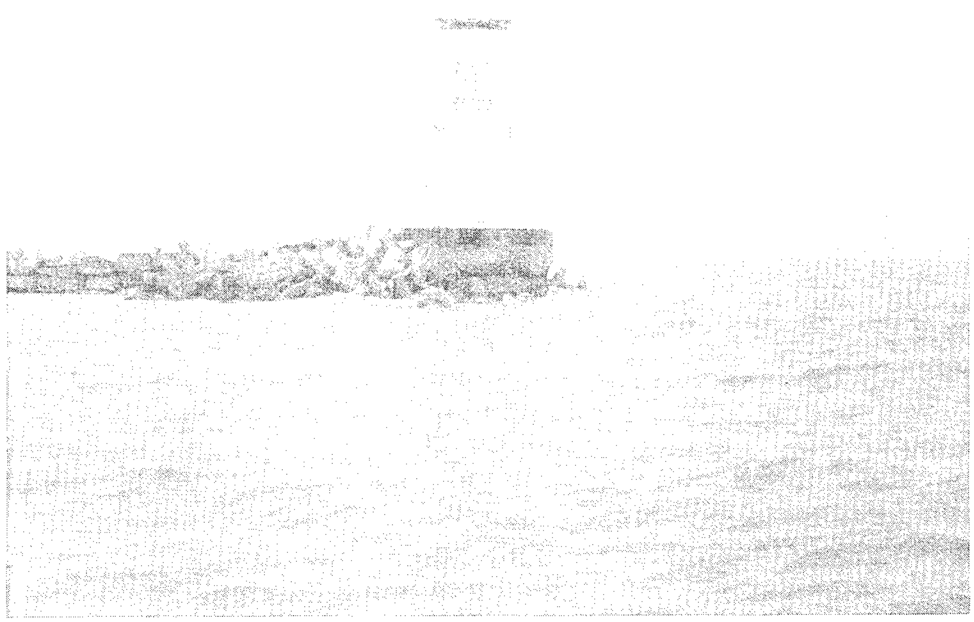


Figure 12. View of head of east breakwater after the 1986-87 winter. Note most the dolos cover is missing

The 1986-1987 storms were not as severe as the April 1982 event, but caused significantly more damage. Dive inspections in the spring of 1987 revealed a significant number of dolos fragments scattered over the underwater slope. These findings suggest that the duration of the storm may be just as important as the incident wave heights. It is conjectured that prolonged rocking of the units may have caused the failure at the east breakwater head during 1987.

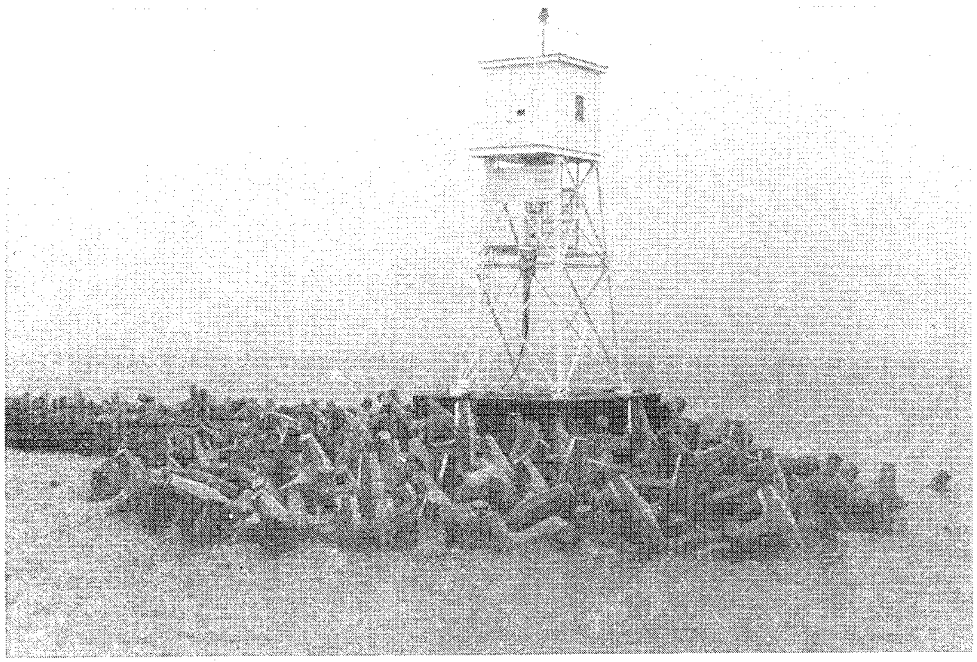


Figure 13. View of 4-ton dolos units placed around head of structure in May 1987

Armor Stone Rehabilitations and Monitoring

Recent rehabilitations

The latest major stone rehabilitations of the Cleveland Harbor East Breakwater occurred in 1985-1986, 1988-1989, and 1992 as shown in Figure 14. The 1985-1986 rehabilitation (sta 188+50-218+00 and 224+00-230+00) involved the placement of 8,165 to 18,144-kg (9 to 20-ton) stone on 1V:1.5H side slopes. A walking inspection of the project in 1988 revealed extensive fracturing of the armor stone placed just three years earlier (Marcus 1993). Breakage of the stone was attributed to blast fractures and the geologic composition of the quarry. As a result, an intensive quality assurance/quality control effort was implemented prior to the 1988-1989 rehabilitation, which consisted of the same size stone and side slopes at sta 107+00-126+50 and 181+50-188+50. The 1992 rehabilitation entailed the installation of 3,900 to 8,709-kg (4.3 to 9.6-ton) stone on 1V:2H side slopes at sta 158+00-170+00 and 218+00-224+00.

Cracked stone monitoring

Recent findings of acutely cracked stone on the Cleveland Harbor East Breakwater has led to attempts to better understand stone durability and the natural and man-made causes are for early stone degradation. The

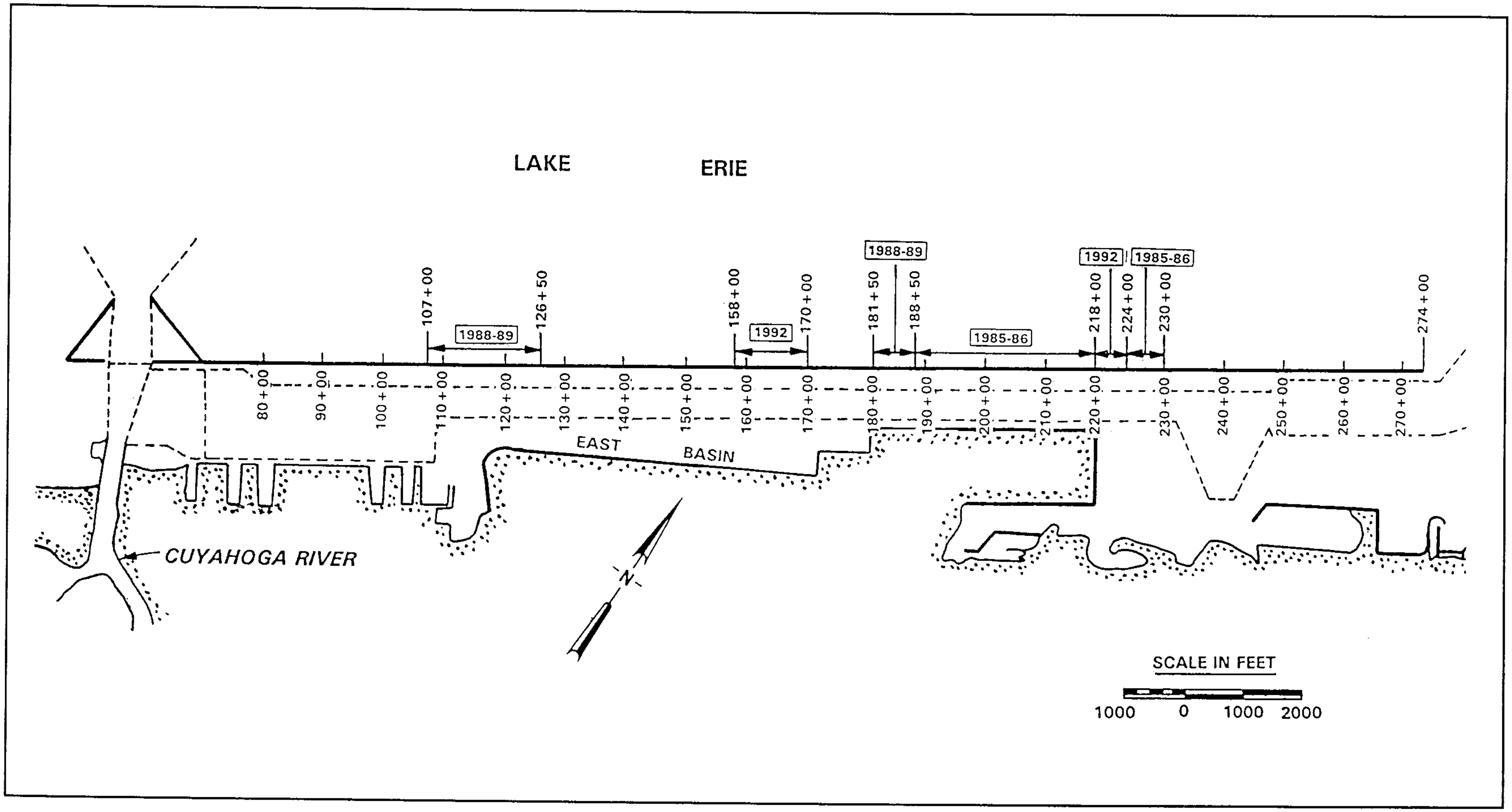


Figure 14. Major stone rehabilitation areas of the east breakwater from 1985-1992

investigation of stone cracking on the east breakwater was initiated in 1989 and is in its fifth consecutive year. A large cracked stone database has been established. This information is providing some insight into the problem; however, stone quality and durability questions still remain unanswered because of the lack of longer-term information. The investigation began as a minimally funded, one-time effort but has gradually increased in scope, and now includes observing and documenting new crack formation and crack damage development with time. This information will help in gaining an understanding of long-term block integrity responses of cracked and cracking stone on breakwater structures.

Initially, three study reaches on three uniquely different stone rehabilitation sections of the Cleveland East Breakwater were selected for monitoring. Detailed geologic stone cracking investigations began at study Reach 1 (sta 197+65-198+65) in 1989. This section was representative of severely cracked stone rehabilitation work completed in 1985-86. In 1990, study Reach 2 was added to the project (sta 107+50-108+50). This section was constructed with the same size stone and delivered by the same supplier as Reach 1; however, this stone was placed only after passing an enhanced Government quality control/quality assurance (QC/QA) operation. In 1992, study Reach 3 (sta 164+00-164+55) was added to the program. This portion of the structure was constructed with smaller stone on a flatter slope with the intention of improving stone durability. The locations of all three study reaches are within the rehabilitation areas shown in Figure 14.

Methods of data collection and documentation

All cracked stone data were obtained by making close visual inspections of each above-water stone during breakwater walking surveys. Simple taping of baselines and offsets were used to locate various stones. This method was cost effective for the limited budget and provided thorough documentation of microcrack and macrocrack damage on each stone. Individual walk-over inspections were found early in the project to reveal minute, not-so-obvious, hairline width cracks and fractures missed during annual boat inspections or less frequent low altitude fly-overs. These minute, but significant, hairline cracks have proved to be significant, and within a year to several years, close inspection has revealed that many cracks open and fragment the stone, destroying the armor units' integrity. All cracks were photographed close up with 35-mm film. Later in the project (1992-93), video documentation was used in viewing through-going crack characteristics and documenting the advanced stages of stone deterioration. Direct photographic comparisons were used successfully and cost effectively to assist in qualifying and quantifying crack formation and crack damage development.

Stone cracking information was recorded onsite and maintained in a field notebook. It then was input into a computer database established for the project. The information documented in the field included the following:

a. Surveyed location of the stone.

b. Number of significant cracks. (A significant crack is defined as a crack opening, no less than 0.3 m (1 ft) in length penetrating through at least two adjacent sides of the stone).

c. Crack damage type. Crack damage has been categorized into four types (A, B, C, or D).

(1) Type "A" damage - The least significant crack damage. It is defined as a crack found throughgoing on at least two sides of the stone, a minimum of 0.3 m (1 ft) long, and projects into at least 20 percent of the stone.

(2) Type "B" damage - The significant crack penetrates completely through the stone. The width of the crack is between hairline thickness and 5.1 cm (2 in).

(3) Type "C" damage - The width of the crack is between 5.1 and 15.2 cm (2 and 6 in).

(4) Type "D" damage - This is the worst crack damage. Crack width is greater than 15.2 cm (6 in) and fragmented displacement is occurring.

d. Location of crack, as related to geology (Marcus 1991).

e. The apparent mechanism for cracking. This is based on stone stress characteristics, man-influenced blast effects (Figure 15) or cracking by natural causes (Figure 16).

f. Additional information and comments (including information on good, uncracked stones).

Significant cracks were spray painted and stones were numbered annually before photographing. This aided in identifying crack damage and evaluating year-to-year comparisons. Stone crack damage photography was attempted from the same angles and distances; however, some difficulties occurred because of lack of proper equipment and time. Sequential annual photos of individual stones in study reaches 1-3 have been obtained and are stored in the CENBC offices. This is the most thorough photographic collection of stone cracking progression and crack damage development of any breakwater in the Great Lakes region.

Data results

A limited non-technical survey in the fall of 1988 revealed that, on a rehabilitation section constructed between 1985 and 1986, about 28 to 43 percent

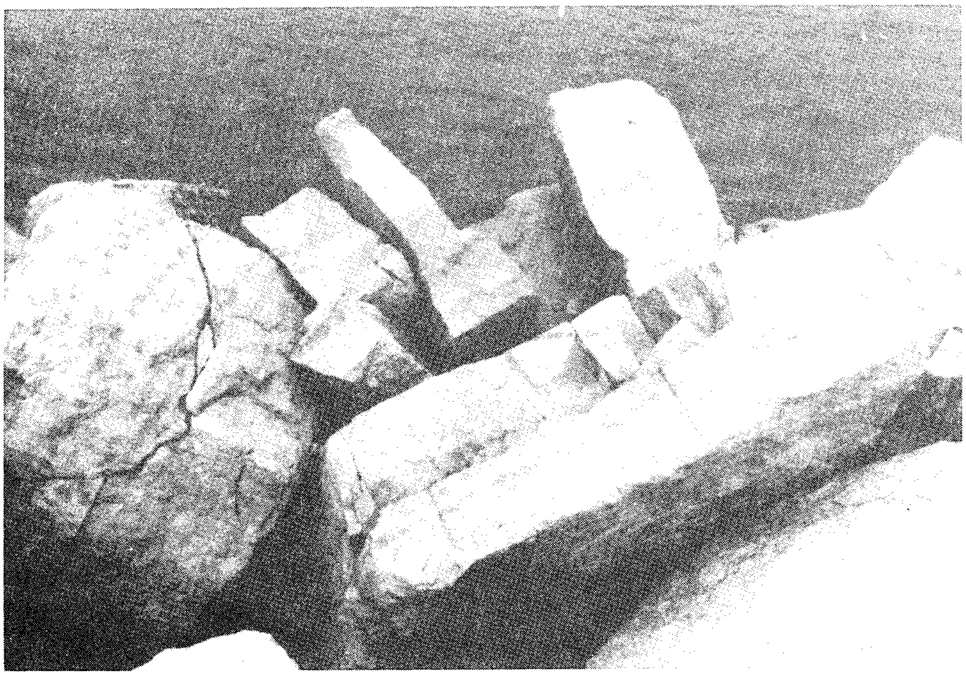


Figure 15. Typical man-influenced blast crack damage observed on all study reaches

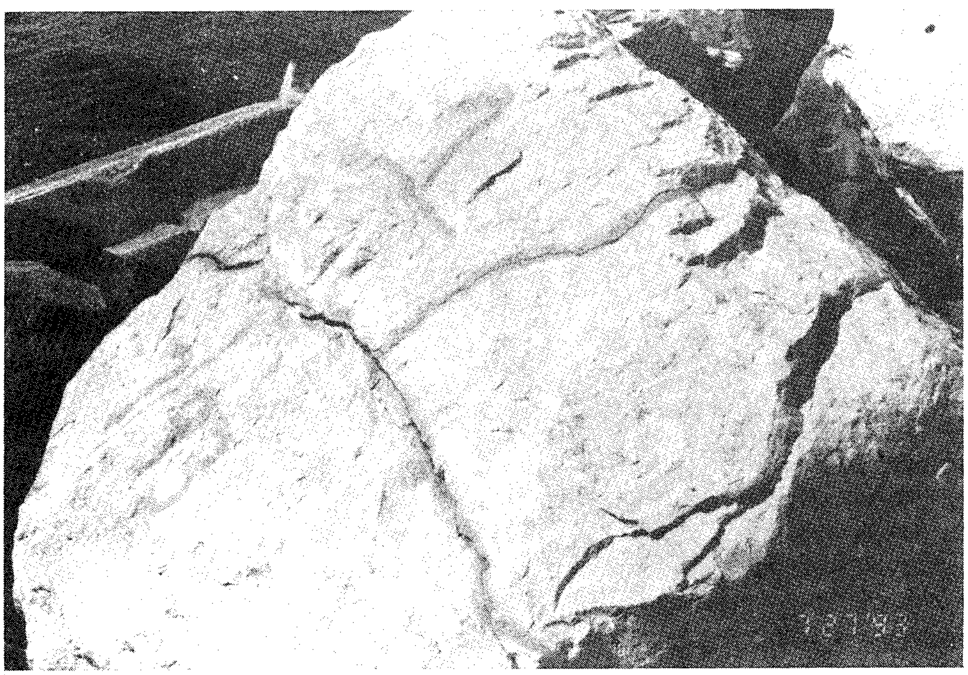


Figure 16. Typical natural mirror image fracturing observed on all study reaches

of all breakwater stones were cracked. Detailed geologic inspections the following year revealed cracked stone percentages far worse than those previously recorded. The geologic inspections indicated that about 80 percent of the stone (8,165 to 18,144-kg (9 to 20-ton) dolomitic limestone blocks) contained one or more significant cracks. These results, in addition to cracked armor on other Great Lakes' structures (Leinhart 1991, Lutton 1991, Marcus 1991), was cause for increased involvement concerning the understanding of large stone durability in coastal environments.

Study Reach 1 (sta 197+65-198+65) has been monitored annually throughout the project and is the best documented of the three study reaches. The Reach 1 evaluations reveal that of 59 stone armor units monitored between 1989 and 1992, random cracking is occurring across the entire profile of the breakwater reach (Figure 17). However, the relative frequency of the crack damage-type is largely skewed to the lakeside of the structure (Figure 18). Over the four years of monitoring, the worst damage classification, type "D," is occurring at or near the waterline. The number of significant cracks has increased with time on both damaged and undamaged stones. Of 12 good stones documented in 1989, two became significantly damaged by 1992; one cracking in each of the 6th and 7th years of exposure. The degree of damage change was highest between 1989 and 1990, likely due to increased storm frequency and duration compared with later years. The apparent mechanism for cracking is about half blast related and half natural. Of 93 cracks documented in study Reach 1, 49 were recorded as blast related (53 percent), and 44 cracks (47 percent) were apparently caused by natural consequences such as freeze-thaw, wet-dry, or other weathering factors. At the end of monitoring in 1992, 83 percent of the stones on study Reach 1 was documented as being cracked.

In 1990 (one year after construction), the enhanced QC/QA effort of study Reach 2 (sta 107+50-108+50) was initially deemed successful because less than 1 percent of the stones monitored revealed crack damage. At the quarry about one-half of the total stone stockpile had been rejected due to blast damage. This correlates closely with the 50 percent apparent blast crack damage recorded in study Reach 1. Evaluations two years after placement revealed 11 percent crack damaged stone on this study section and along additional portions of the rehabilitation. Similar to study Reach 1, cracking was observed randomly occurring throughout the structure. A small number of developing blast cracks were found and notes from the enhanced QC/QA program reveal that these damaged stones were often marginally passed. Three years of documentation on study Reach 2 indicated that the enhanced QC/QA operation has significantly reduced the amount of blast damaged stone placed on the structure; however, natural cracking is still occurring. Study Reach 2 had a significantly lower cracking rate after three years of exposure (18 percent) as compared with the 83 percent cracked stone damage on study Reach 1 after four years. In addition, only 10 percent of the cracked stones on study Reach 2 have multiple cracks as opposed to about 50 percent on study Reach 1. A comparison of the percentage of cracked stones versus years of exposure for study Reaches 1 and 2 is shown in Figure 19.

Study Reach 3 (sta 164+00-164+55) entailed smaller stone installed on a flatter slope delivered by a different source (quarry). The rehabilitation was

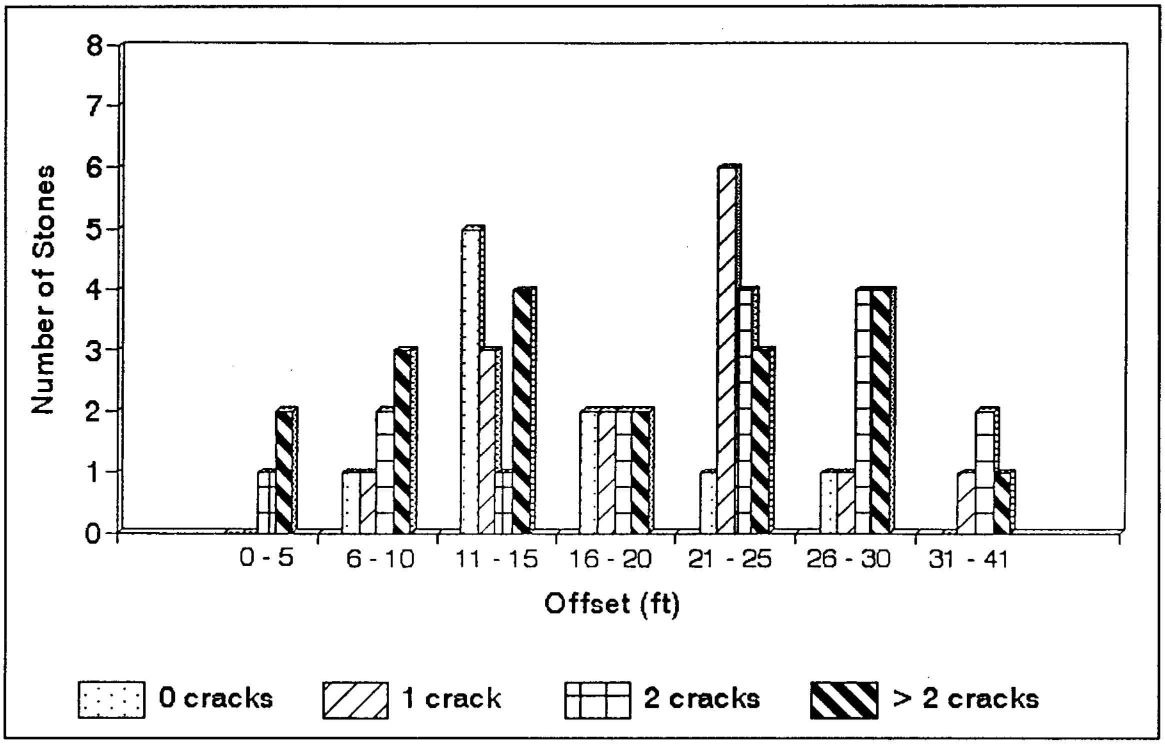


Figure 17. Cracked stone distribution along study Reach 1

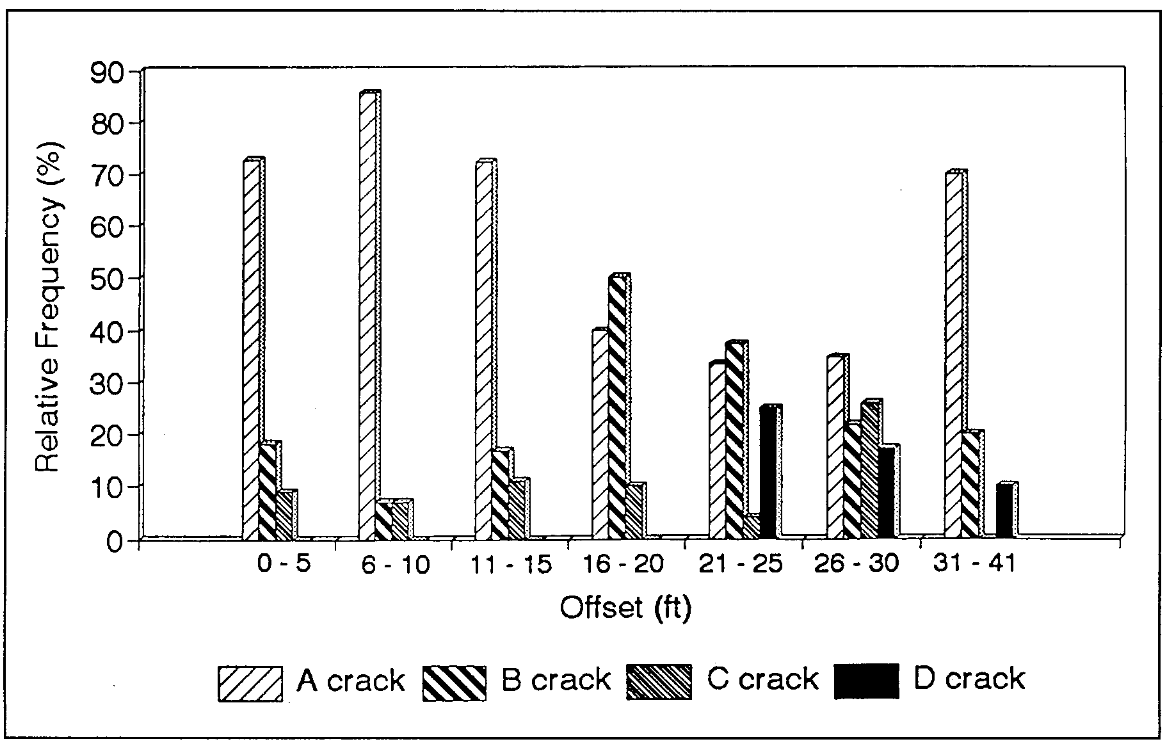


Figure 18. Relative frequency crack damage-type distribution versus offset distance from baseline

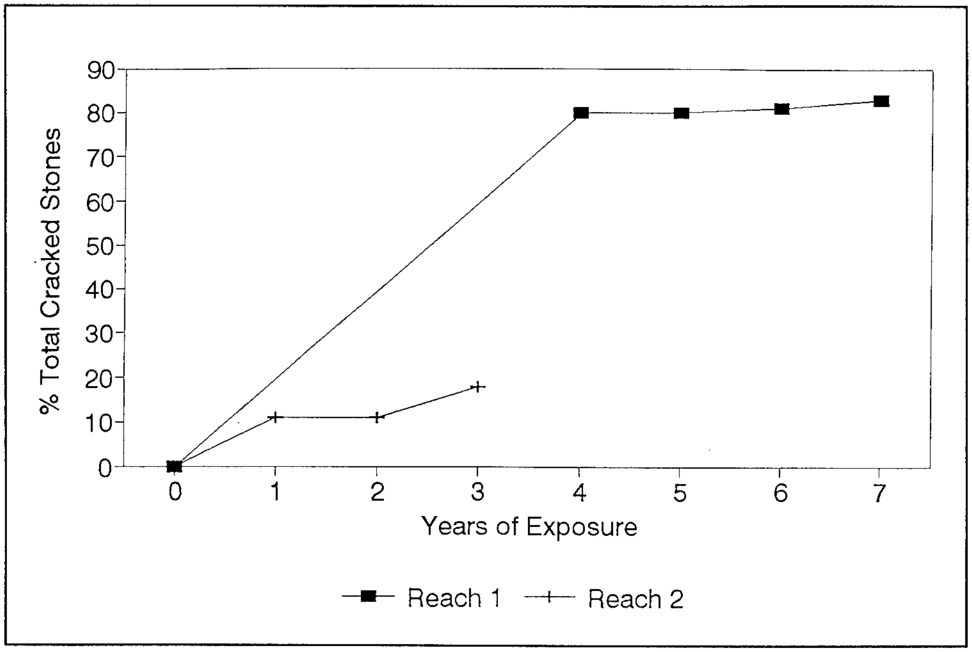


Figure 19. Cracked stones for study Reach 1 versus study Reach 2

completed in 1992, and the standard Corps QC/QA practice was used. After the first year of exposure, 3 of 54 stones monitored (6 percent) had developed significant cracks. Two of these 3 stones had blast fractured cracks (Figure 20). Documentation of the 54 individual stones was conducted with videotape this season instead of 35-mm photography due to budget constraints.

Figure 20. Blast-fractured stone of study Reach 3 after one exposure season

Conclusions from previous stone monitoring

Four consecutive years of monitoring cracked stone on three uniquely different reaches of the Cleveland Harbor East Breakwater resulted in the following conclusions:

a. Detailed geologic cracked stone investigations performed during breakwater walking inspections proved to be a successful method for observing minute crack formation and crack damage development otherwise missed by routine boat or aerial observation.

b. The sequential photographing of individual stone damage on an annual basis, with cracks and crack damage spray painted and recorded, has provided viable, visual documentation of the stone cracking problem occurring on the breakwater.

c. Annual photographic sequences and photographic comparisons proved to be a highly successful tool in assisting with quantification of damage-type over time.

d. Breakage of armor stone occurs along the entire profile of the structure; however, most type-D breakage (where displacement of stone pieces occurs) takes place along the waterline, in the active wave zone.

e. Early indications suggest that enhanced QC\QA stone inspections yield better end quality products than the current standard Corps QC\QA inspections.

f. As evidenced by continued cracking and crack damage advancement, a severe problem exists on the above-water armor stone on the East Breakwater. Further studies using the completed database may provide new insight on the future of stone durability in coastal structures.

3 Current Monitoring Plan and Data

The objective of the monitoring effort in the Periodic Inspections work unit was to reexamine the Cleveland Harbor East Breakwater and determine changes that have occurred since the MCCP program ended in 1985, and to establish base level data upon which long-term stability response of the east breakwater can be defined through periodic inspections. The eastern 1,341 m (4,400 ft) of the structure (sta 230+00-274+00) was to be monitored as well as three representative sections of recent stone rehabilitations. Sections of the 1985-1986, 1988-1989, and 1992 rubble rehabilitations selected by CENCB as representative were sta 197+35-199+15, sta 107+10-108+90, and sta 163+40-165+20, respectively. The monitoring plan consisted of broken armor unit surveys, targeting and ground surveys, low-altitude aerial photography, and photogrammetric analysis of armor units.

Broken Armor Unit Surveys

During the period 27 July-2 August 1993, a survey of broken/cracked armor units above the waterline on the Cleveland Harbor East Breakwater was conducted. The inspection included the dolos-armored 1,341-m (4,400-ft) eastern portion of the structure and three sections of stone-armored breakwater. During the inspection, each broken armor unit was identified and photographed, and its location relative to the breakwater station and offset from a baseline was recorded. The water was relatively clear during the survey, and the lake level was approximately +1.1 m (+3.6 ft) LWD (IGLD85).

Dolos armor

For the dolos armor, the number and date of casting, if visible, were recorded as well as the type of break and break separation distance (approximate distance separating dolos parts). Types of breaks included shank and fluke breaks. They were characterized as mid-shank, shank-fluke (shank broken in vicinity of fluke), and fluke-shank (fluke broken off at junction with shank). Also recorded were straight breaks (broken straight across) and angled breaks (broken at some angle to the dolos limb). Views of representative types of breaks are shown in Figures 21-23. Many dolos fragments were observed, however, broken dolosse were not counted unless at least one-half of the unit was present. An example of the data recorded is shown in Figure 24.

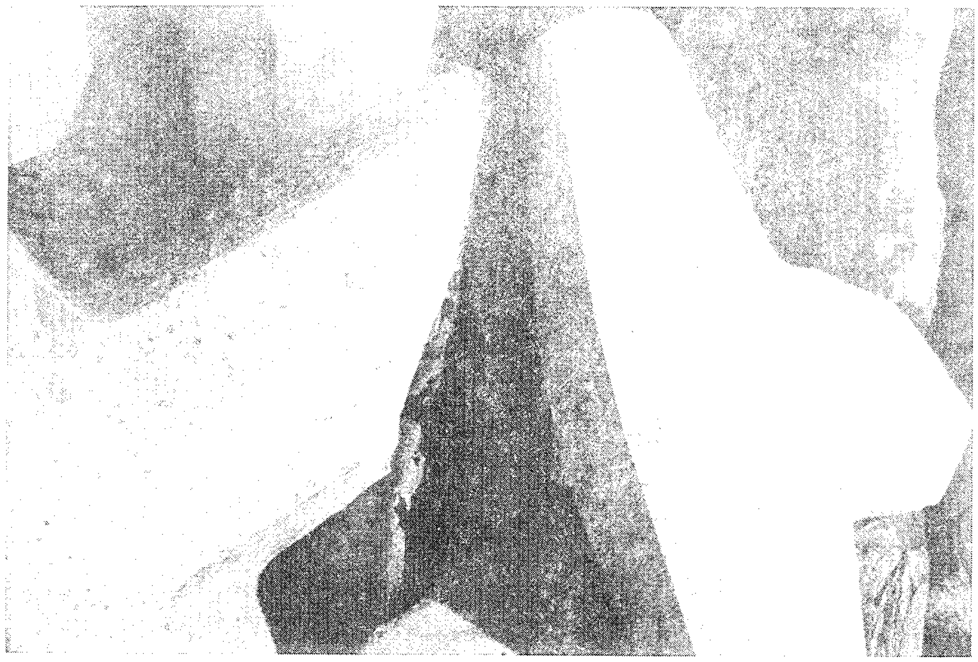
Evaluation of the survey results indicates 782 broken/ cracked dolos above the waterline. Eighteen broken units were observed around the east breakwater head with the remaining units along the trunk. Of the 18 broken/cracked armor units identified at the head, four were 3,628-kg (4-ton) dolos. Three additional broken 3,628-kg (4-ton) units were observed along the breakwater trunk. The distribution of broken dolos along the breakwater trunk as a function of station number and offset from the baseline was analyzed. (The baseline was approximately the lakeward edge of the existing capstone along the breakwater crest.) Figure 25 shows the locations of broken/cracked dolos relative to the station number. As shown, broken units occur along the entire trunk section and are not, in general, concentrated in any one particular area. The distribution of broken/cracked armor units relative to offset from the baseline is shown in Figure 26. The majority of the broken dolos along the breakwater trunk (80 percent) are located between 1.8 and 6.1 m (6 and 20 ft) lakeward of the baseline. These units are in the active wave zone. Comparison of broken units to production data indicated that no particular production group had an unusual amount of breakage.

Of the 782 broken/cracked dolos, 48 units had multiple breaks. Therefore, the 782 broken units actually yielded 833 total breaks. The types of breaks were analyzed, and the majorities were determined to be shank-fluke breaks (494 breaks or 59.3 percent). There were 260 fluke-shank breaks (31.2 percent) and 79 mid-shank breaks (9.5 percent). Considering all the breaks, 417 were straight and 416 were angled.

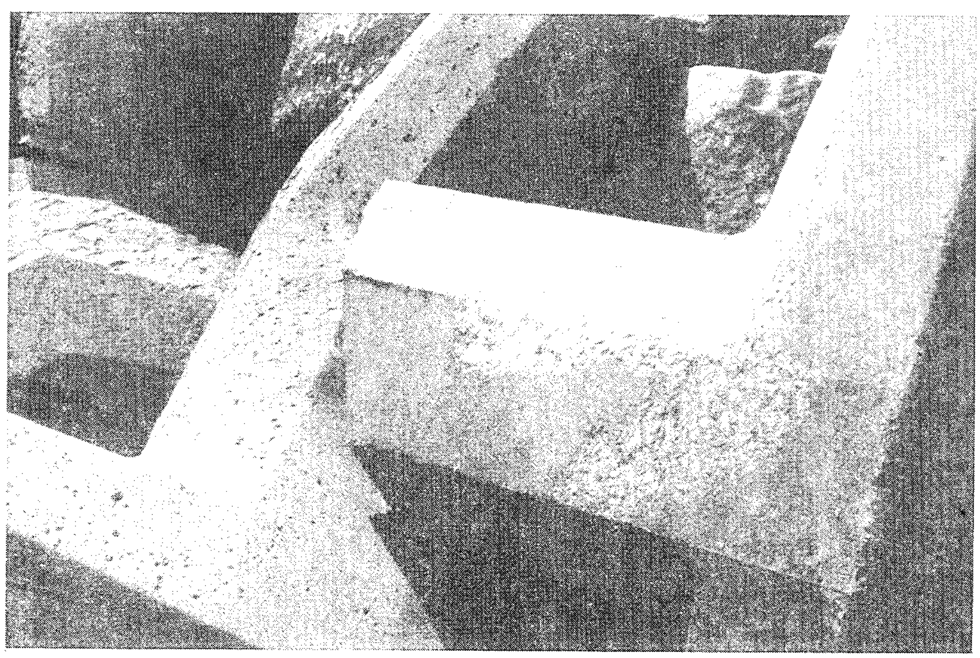
It is obvious that the rate of breakage of dolosse on the breakwater has drastically decreased, as opposed to the period after initial construction. During the 5-yr monitoring period after initial construction (1980-1985), 692 units were identified as broken/cracked. During the following 8-year period (1985-1993), the total number of broken units was 782. However, it was apparent from dolos remnants found along the structure that many of the broken units identified in the earlier survey were not counted during the latter. Some of the previous broken unit fragments had fallen into voids in the breakwater, and portions have probably been swept by wave action downslope underwater out of view. Also, broken units around the head were lost during the 1986-87 winter storms. The detailed data obtained during the current survey (1993) will allow for an accurate indication of new breaks when the structure is revisited at some point in the future.

Stone armor

For the broken stone armor unit surveys, sections of each reach were monitored and armor stone crack formation and damage development were

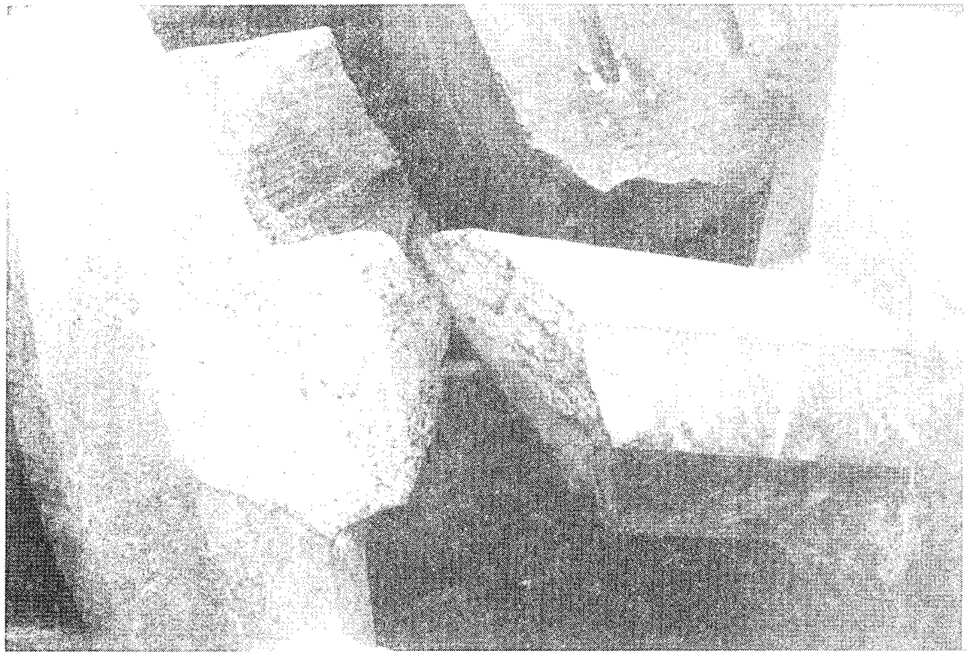


a. Angled mid-shank break

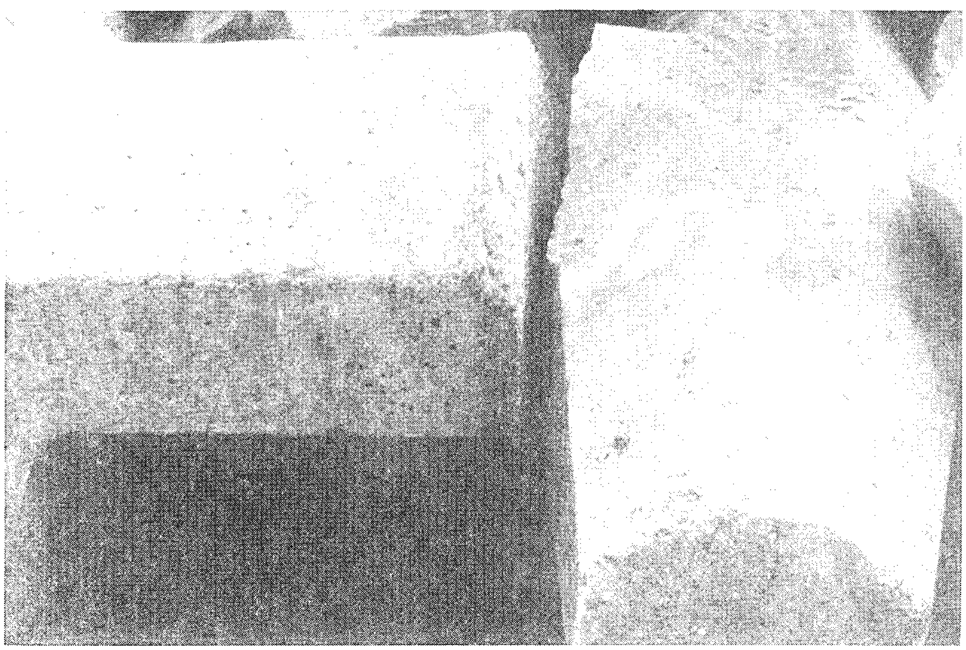


b. Straight mid-shank break

Figure 21. Dolosse with straight and angled mid-shank breaks

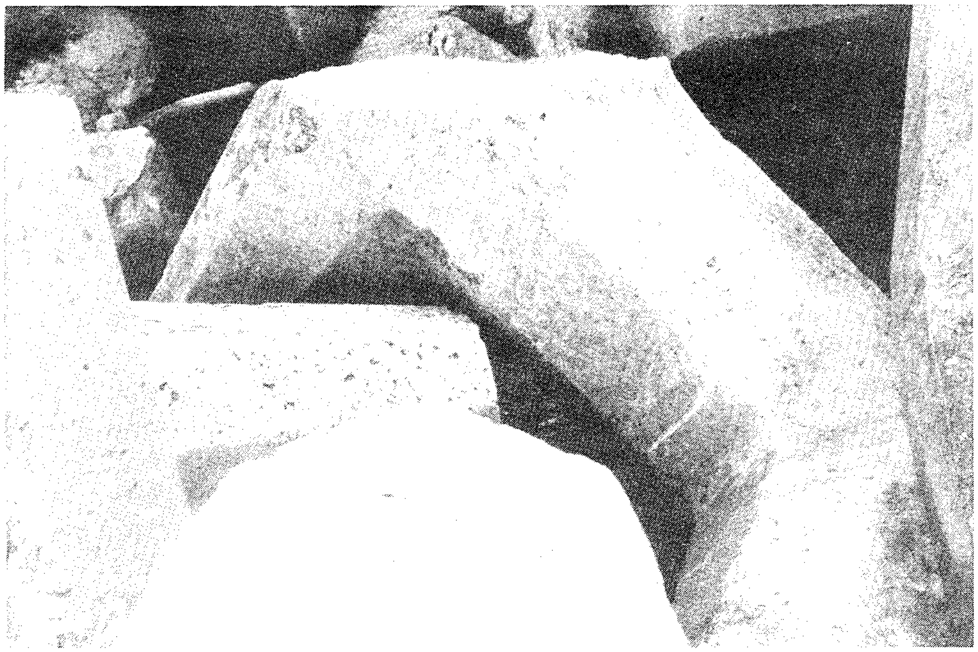


a. Angled shank-fluke break

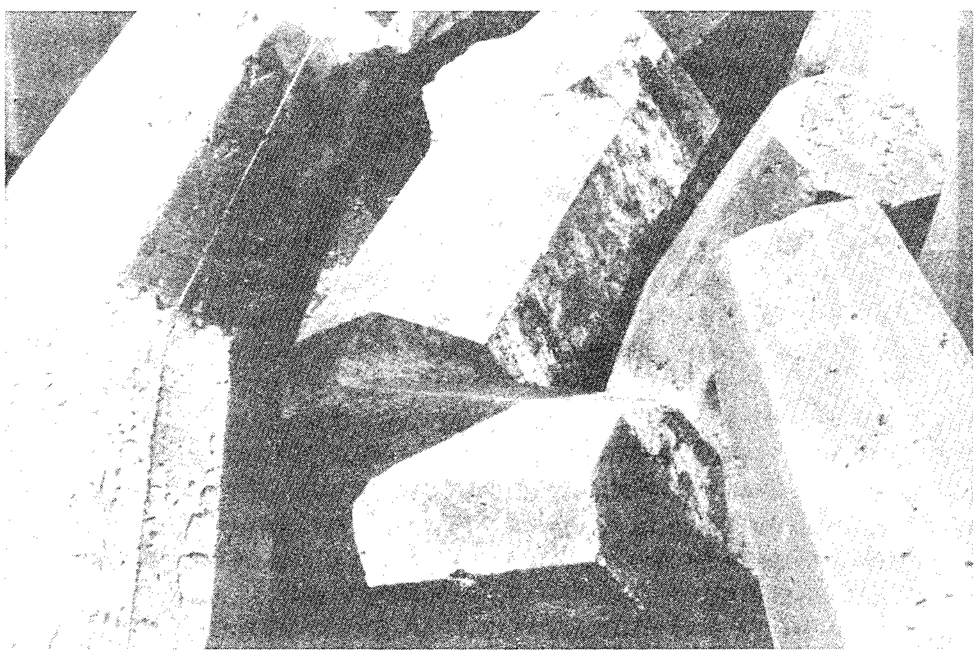


b. Straight shank-fluke break

Figure 22. Dolosse with straight and angled shank-fluke breaks



a. Angled fluke-shank break



b. Straight fluke-shank break

Figure 23. Dolosse with straight and angled fluke-shank breaks

Dolos Number	Station	Offset from Base-line	Dolos Production		Type of Break	Break Separ. Dist.	Roll-Photo Number	Comments
			Number	Date				
56	270+67	19	4406	1-8-80	FS-S	U	3-15	@WL
57	270+57	16	NV	NV	FS-S	U	3-16	@WL
58	270+80	0	NV	NV	SF-A	U	3-17	
59	270+65	5	4300	1-7-80	FS-S	3'	3-18	
60	270+43	2	4351	1-7-80	FS-S	3'	3-23	
61	270+40	6	NV	NV	FS-A	U	3-21	
62	270+62	5	NV	NV	MS-A	U	3-22	
63	270+40	9	NV	NV	MS-S, FS-S	U,U	3-24	
64	270+22	0	NV	NV	FS-S, SF-S	U,2'	4-1	
65	270+22	7	4334	2-13-80	SF-S	6"	4-2	
66	270+14	6	5112	2-2-80	SF-S	3'	4-3	
67	270+02	1	NV	NV	SF-S	6"	4-4	
68	270+00	6	NV	NV	SF-S	6"	4-5	
69	269+87	5	NV	NV	SF-S	U	4-6	
70	269+73	4	5762	1-22-80	SF-S	3'	4-7	
71	269+68	14	NV	NV	SF-S	U	4-8	NO NUMBER

LEGEND

NV - not visible, FS-S - fluke shank straight, FS-A - fluke shank angled, SF-S - shank fluke straight

SF-A - shank fluke angled, MS-S - mid shank straight, MS-A - mid shank angled, U - undetermined, WL - water line

Figure 24. Example of data recorded during armor unit survey

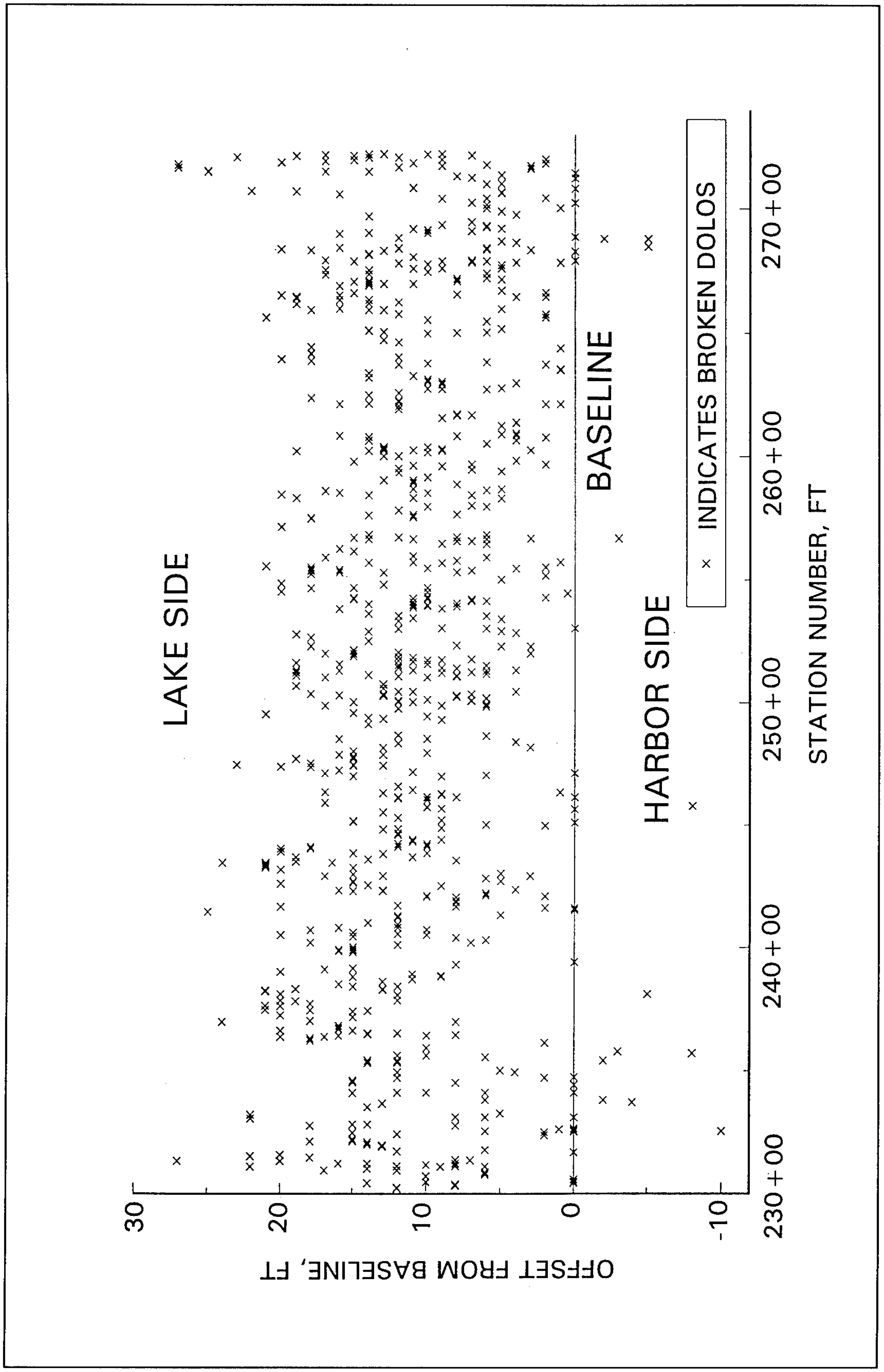


Figure 25. Distribution of broken dolos armor units along breakwater trunk relative to station number

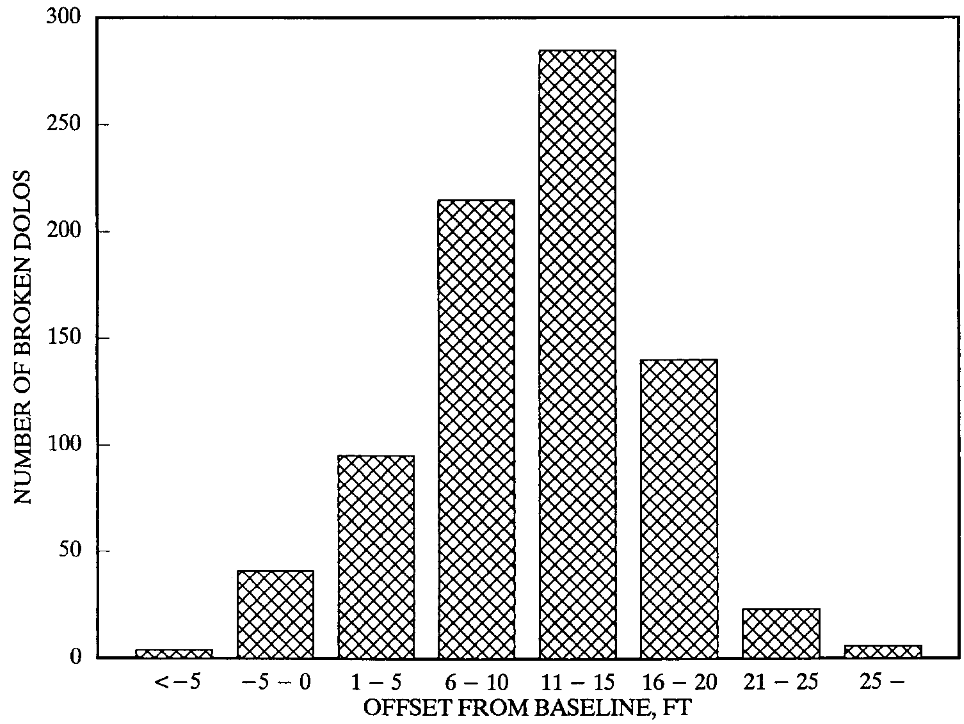


Figure 26. Distribution of broken dolos armor units relative to distance from baseline

documented. The length of structure monitored in 1993 more than doubled what was studied in previous years. Reaches 1, 2 and 3 now include sta 197+65-200+00, sta 107+50-109+50 and sta 163+60-165+40, respectively.

Study Reach 1 included a new 41.1-m (135-ft) section (sta 198+65-200+00) in addition to the adjacent historical reach study area (sta 197+65-198+65) monitored from 1989-1992. Over the entire 71.6-m (235-ft) study section, full documentation of 148 stones (8,165 to 18,144-kg (9 to 20-ton) dolomitic limestones) has been completed. Of the 59 previously reviewed stones in the historical reach study area, no new damage occurred on the 10 undamaged stones. However, continued cracking and increased crack damage-types were recorded similar to past surveys. New cracking is also occurring randomly. On the new section, monitoring indicated that 61 of 89 stones (68.5 percent) contained one or more significant cracks. A total of 110 significant cracks were recorded along the entire new study reach. Damage was found to be randomly scattered across the profile of the breakwater similar to the original study region. The crack damage-type distribution was also randomly scattered, but the more severe "D" cracks were again prevalent in the active wave zone. A total of 39 stones (44 percent) had two or more cracks. Considering the entire 71.6-m (235-ft) study reach, 74 percent (110 of 148) of the above-water stones on study Reach 1 were documented as being cracked.

Study Reach 2 involved monitoring an additional 30.5-m (100-ft) section (sta 108+50-109+50) adjacent to the historical reach area (sta 107+50-108+50) monitored from 1990-1992. Over the entire 61-m (200-ft) study reach, full documentation of 129 stones (8,165 to 18,144-kg (9 to 20-ton) dolomitic limestones) was completed. This is an area where the enhanced QC/QA effort was conducted prior to construction. Stone crack damage in study Reach 2 was similar to the previous year. Of the 129 stones investigated, 19 percent were considered unsatisfactory because of significant crack damage (versus 18 percent previously), indicating that new crack formation may be leveling off. Of the 24 damaged stones documented, 19 stones (79 percent) had natural mirror image fracturing characteristics, and 5 stones (21 percent) revealed multiple blast fractures. It appears that the enhanced QC/QA process at study Reach 2 has significantly reduced the total crack damage, and most importantly, reduced the detrimental multiple cracking associated with man-induced blasting processes. A comparison of study Reach 1 and 2 reveals a cracking rate of 74 percent for Reach 1 versus 19 percent for Reach 2 considering the total areas monitored in the current effort.

Study Reach 3 entailed monitoring 54.9 m (180 ft) of the structure (sta 163+60-165+40) as opposed to 16.8 m (55 ft) (sta 164+00-164+55) monitored in 1992. Over the 54.9-m (180-ft) study area, monitoring of 152 stones (3,900 to 8,700-kg (4.3 - 9.6-ton) dolomitic limestones) was performed. Of the 152 stones documented, 35 had developed significant cracks (23 percent). The damage was scattered randomly across the breakwater profile similar to study Reaches 1 and 2. Of the 35 damaged stones, 28 (80 percent) was due to blasting fractures. Most of the blast damaged stone contained two or more cracks. Some blast cracks were very obvious due to damage with radial fracturing occurring directly off the cast holes. The remaining seven fractured stones were due to natural mirror image fracturing or bedding plane cracks along shale seams. In summary, 23 percent of the above-water stones in study Reach 3 had significant cracks just two years after exposure. It is noted that standard, not enhanced QC/QA practices were used for acceptance of this stone.

Targeting and Ground Surveys

Monuments were established on land and on the cap of the breakwater to serve as control points (both horizontal and vertical reference) for ground based survey work as well as photogrammetric work. Ground surveys were initiated on known monuments which included National Geodetic Survey stations 1702 and G321 as shown in Figure 27. Using global positioning system (GPS) control surveying and electronic land surveying techniques, monuments were established on the structure. The survey control diagram is shown in Figure 27. GPS positions were established on existing Corps of Engineers monuments 27, 808, 809, 810, and 813 and new monuments RBD1-RBD15 located at approximately 152-m (500-ft) intervals along the study areas. New monuments were established by permanently cementing 7.6-cm (3-in.) brass

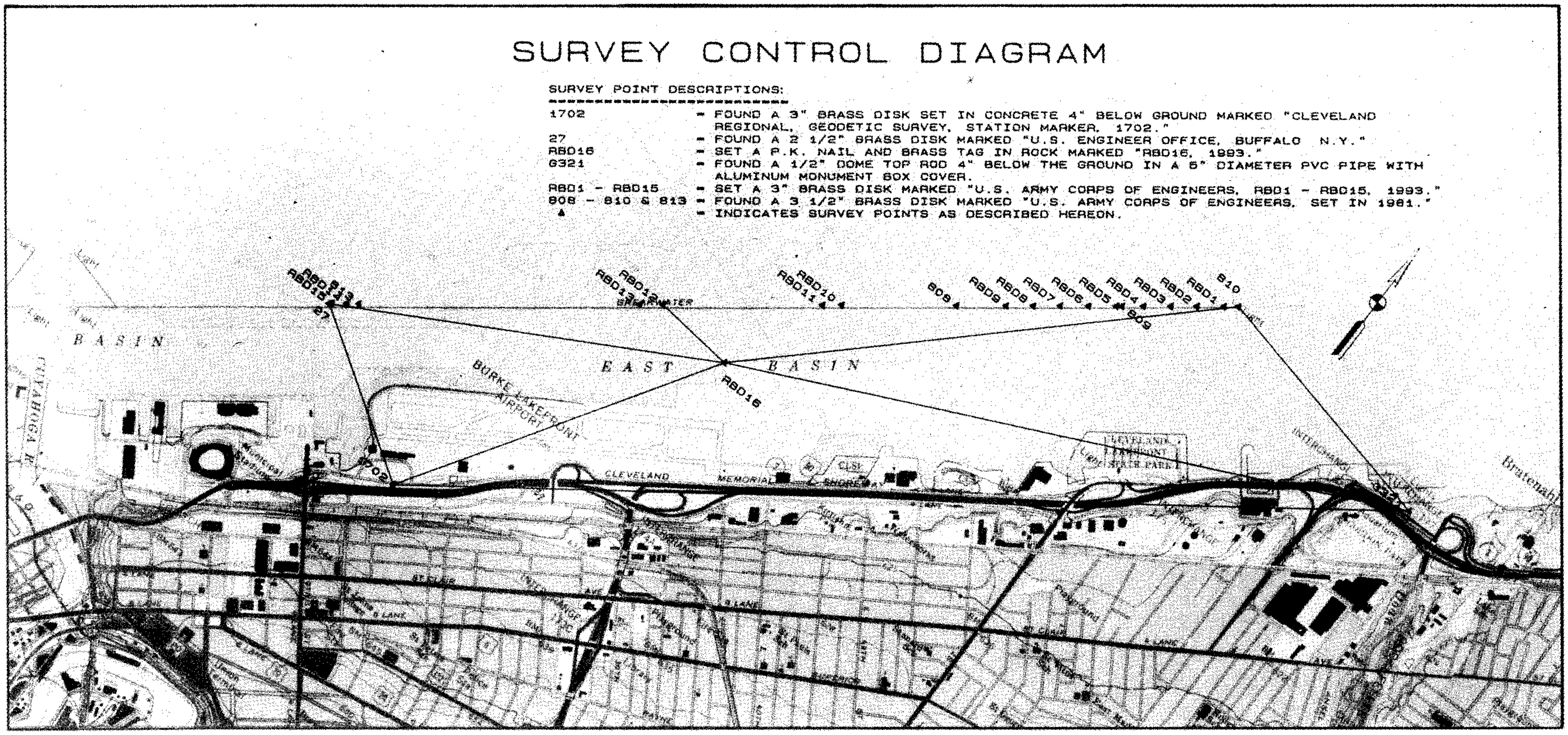


Figure 27. Survey control diagram for monuments established on breakwater

disks in the structure. Positions of the monuments are shown in the following tabulation:

Monument	Easting	Northing	Elevation	Station	Offset
1702	2190621.17	672734.83	583.50	118+10.56	3303.41S
G321	2205531.66	683682.40	583.33	303+03.48	6267.82S
27	2187673.58	674633.95	577.84	106+34.82	0.00
808	2196747.34	681624.86	577.38	220+89.34	0.49S
809	2199140.85	683469.78	578.75	251+11.36	0.04N
810	2200824.79	684767.24	583.53	272+37.16	0.00
813	2188107.18	674968.53	579.45	111+82.50	0.38N
RBD1	2200613.46	684604.44	579.04	269+70.40	0.02N
RBD2	2200222.37	684303.05	578.03	264+76.65	0.01S
RBD3	2199845.75	684012.92	578.52	260+01.24	0.04N
RBD4	2199449.74	683707.77	579.09	255+01.30	0.03N
RBD5	2199053.71	683402.56	578.63	250+01.30	0.02S
RBD6	2198657.31	683097.03	577.71	245+00.82	0.09S
RBD7	2198253.45	682785.74	577.76	239+90.91	0.18S
RBD8	2197863.20	682484.95	577.27	234+98.20	0.25S
RBD9	2197468.63	682180.77	578.26	229+99.99	0.38S
RBD10	2195073.31	680342.83	578.56	199+80.80	5.73S
RBD11	2194801.37	680130.05	578.90	196+35.52	3.16S
RBD12	2192512.87	678361.47	579.95	167+43.27	0.99S
RBD13	2192165.53	678100.29	576.46	163+08.72	4.12N
RBD14	2187929.05	674831.07	578.67	109+57.50	0.22N
RBD15	2187710.78	674662.65	578.55	106+81.81	0.03N
RBD16	2194043.51	678211.45	582.06	178+64.17	1054.07S

Horizontal positions shown are based on the Ohio State Plane Coordinate System and all elevations are referenced to North American Vertical Datum, 1988 (NAVD88)[1]. Station numbers are relative to the breakwater station, and offset is length (feet) north or south of the baseline. The baseline for stationing purposes was a line between monuments 27 and 810 on the breakwater.

In addition to the monuments, targets were established at intervals of about every 18.3 m (60 ft) along the lakeside, landside, and approximate center of the breakwater for the length of each study area. Each station was marked with a drill hole 0.64 cm (1/4-in) in diameter, and 0.64 cm (1/4-in) deep, and painted with a circular target to ensure visibility in the aerial photography. A total of 267 targets were established during this effort. They were electronically surveyed to form control by which the accuracy of the photogrammetric survey work could be validated and defined. The ground survey work was completed in early October 1993. A typical monument and target established on the breakwater are shown in Figures 28 and 29.

[1] To convert NAVD88 to IGLD85 subtract 0.7 m (0.23 ft) i.e., LWD = 173.57 m (569.43 ft) based on NAVD88 and 173.5 m (569.2 ft) based on IGLD85.

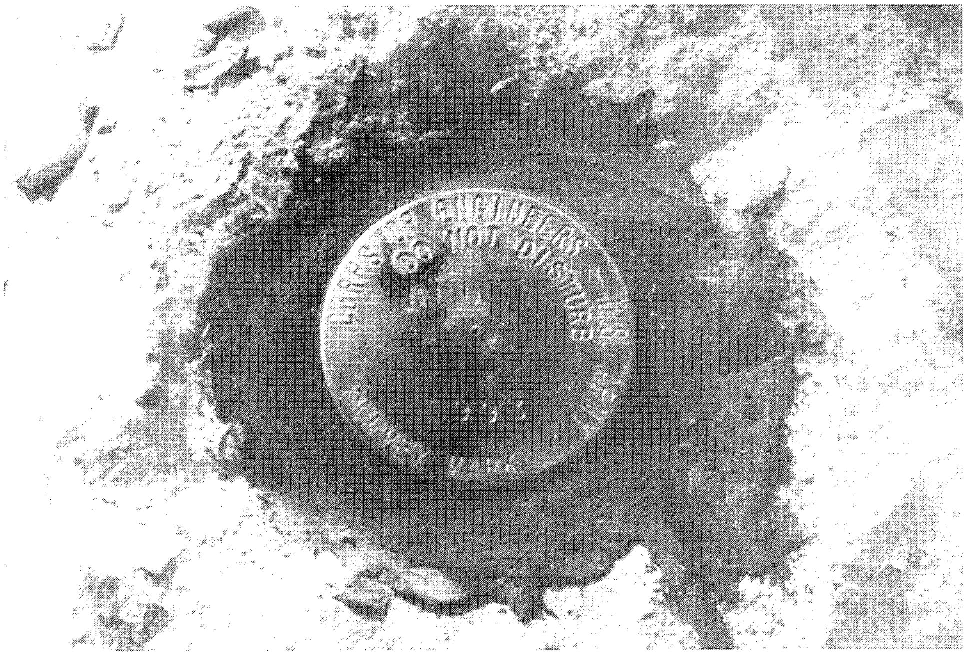


Figure 28. Example of a monument set on Cleveland Harbor Breakwater

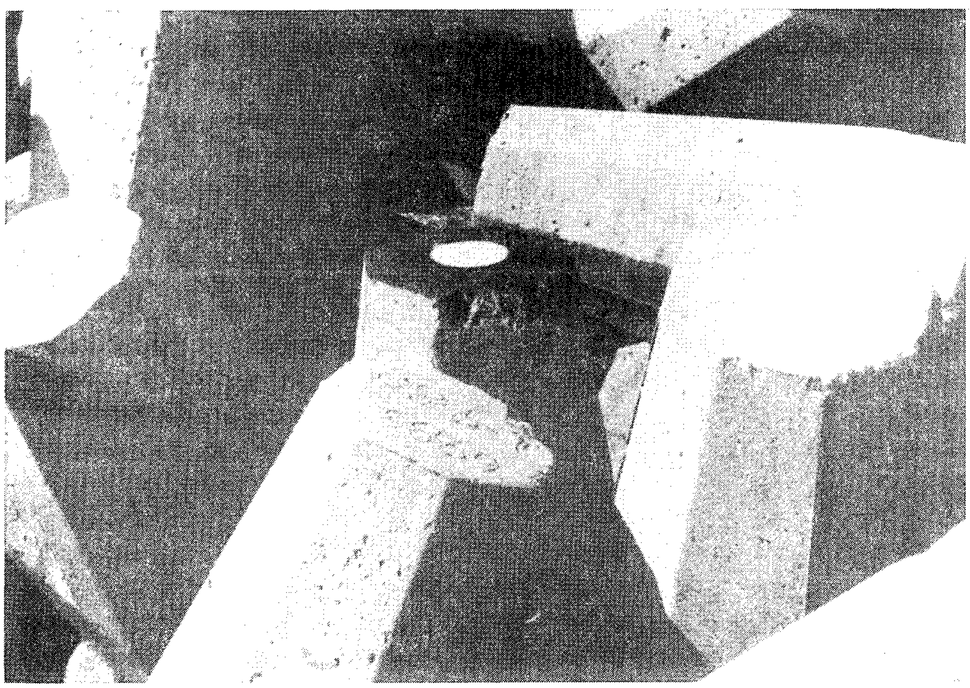


Figure 29. Example of a target established on Cleveland Harbor Breakwater

Low-Altitude Aerial Photography

Aerial photography is a very effective means of capturing images of large areas for later analysis, study, visual comparison to previous or subsequent photography, or measurement and mapping. Its chief attribute is the ability to freeze a moment in time, while capturing extensive detail.

Aerial photography was obtained along the areas of the breakwater being monitored with a Wild RC-8 aerial mapping camera (22.9-cm by 22.9-cm (9-in. by 9-in.) format). The photos were secured from a helicopter flying at low altitude (36.3 m (120 ft)), which resulted in high resolution images and contact prints with scales of 2.54 cm (1 in.) on the photograph equal to 6.1 m (20 ft) in the prototype. The helicopter used for the aerial photography is shown in Figure 30. Photographic stereo pairs were obtained during the flights. Typical stereo pairs for a portion of the dolos armored breakwater and a portion of the stone armored structure are shown in Figures 31 and 32, respectively. The aerial photography was obtained on 14 October 1993. The lake level during the conduct of the photography was +0.82 m (+2.7 ft) lwd (IGLD 1985).

Photogrammetric Analysis of Armor Units

When aerial photography is planned and conducted so that each photo image overlaps the next by 60 percent or more, the two photos comprising the overlap area can be positioned under an instrument called a stereoscope, and viewed in extremely sharp three-dimensional detail. If properly selected survey points on the ground have previously been targeted and are visible in the overlapping photography, very accurate measurements can be obtained of any point appearing in the photos. This technique is called photogrammetry.

The low-altitude stereo pair images obtained during aerial photography at Cleveland were viewed in a stereoscope, and stereomodels were oriented to the monument and target data previously obtained. In the stereomodel, very accurate horizontal and vertical measurements can be made of any point on any armor unit appearing in the print. Maximum differences between the ground and stereomodel elevations were 7.92 mm (0.026 ft) in the easting, 9.45 mm (0.031 ft) in the northing, and 4.57 mm (0.015 ft) in the vertical directions. In general, typical differences were much less, thus the stereomodel was very accurate as evidenced by verification with the ground control survey. The stereomodel was used for all photogrammetric compilation and development of orthophotography.

Orthophotos combine the image characteristics of a photo with the geometric qualities of a map. The digital orthophoto is created by scanning an aerial photo with a precision imagine scanner. The scanned data file is digitally rectified to an orthographic projection by processing each image pixel. Orthophotos were prepared for the cumulative 1,506 m (4,940 ft) of the monitored breakwater at Cleveland. Examples of orthophotos for portions of the dolos- and stone-armored breakwater are presented in Figures 33 and 34, respectively. Precise horizontal measurements may be obtained from the orthophotos using an engineer scale since the image has been rectified and is free from skewness and distortion.

Figure 30. Views of helicopter used to obtain low-altitude, high resolution aerial photography

In addition to digital orthophotos, point plot maps, contour maps, and cross sections were developed for the monitored portions of the breakwater using digital terrain model (DTM). The point plot maps consisted of a 0.3-m (1-ft) grid pattern overlaid on the structure. Precise vertical and horizontal measurements were obtained at the intersections of the grid. Point plot maps showing elevations for portions of the dolos- and stone-armored breakwater are shown

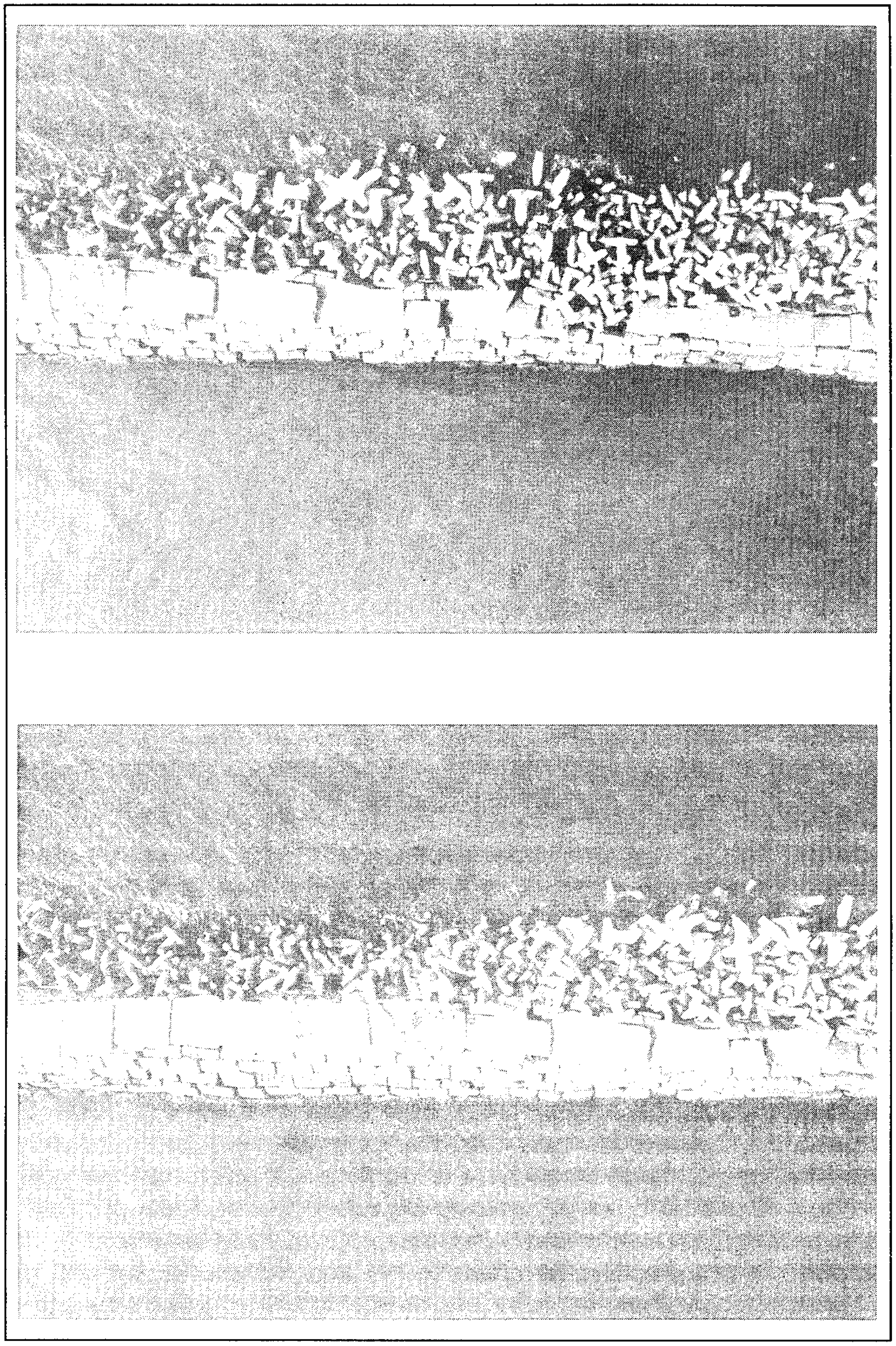


Figure 31. Stereo pair photos for a portion of the dolos-armored breakwater

in Figures 35 and 36. Areas where no elevations are shown are shadowed areas between the armor units. Contour maps of the areas of the breakwater monitored were then developed from the DTM grid. Examples are shown in

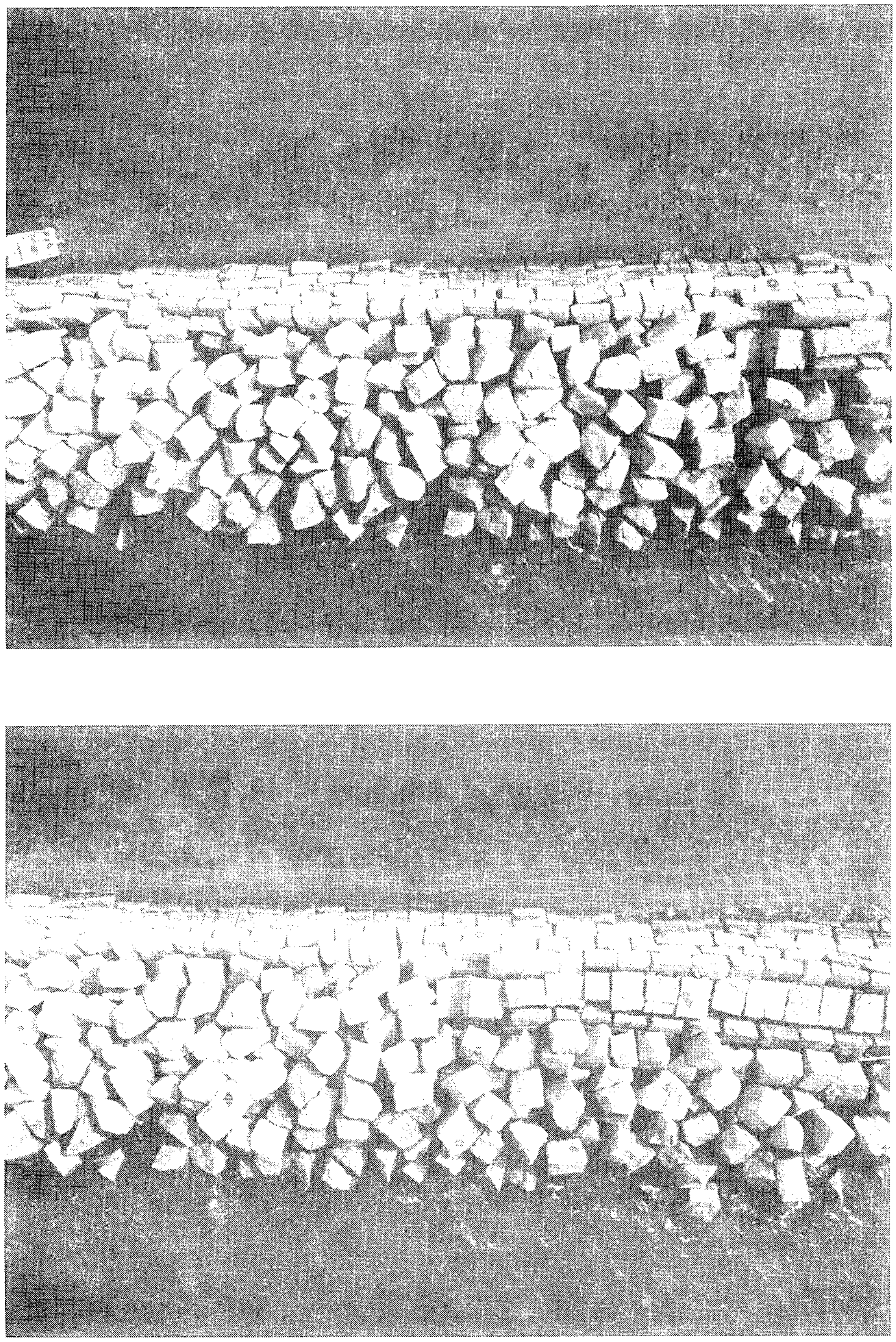


Figure 32. Stereo pair photos for a portion of the stone-armored breakwater

Figures 37 and 38 for the dolos- and stone-armored breakwater, respectively. The contours were generated on 0.3-m (1-ft) intervals. Additionally, using the analytical stereoplotter and DTM grid, cross sections of the breakwater were generated. These sections were provided at 61-m (200-ft) intervals along the

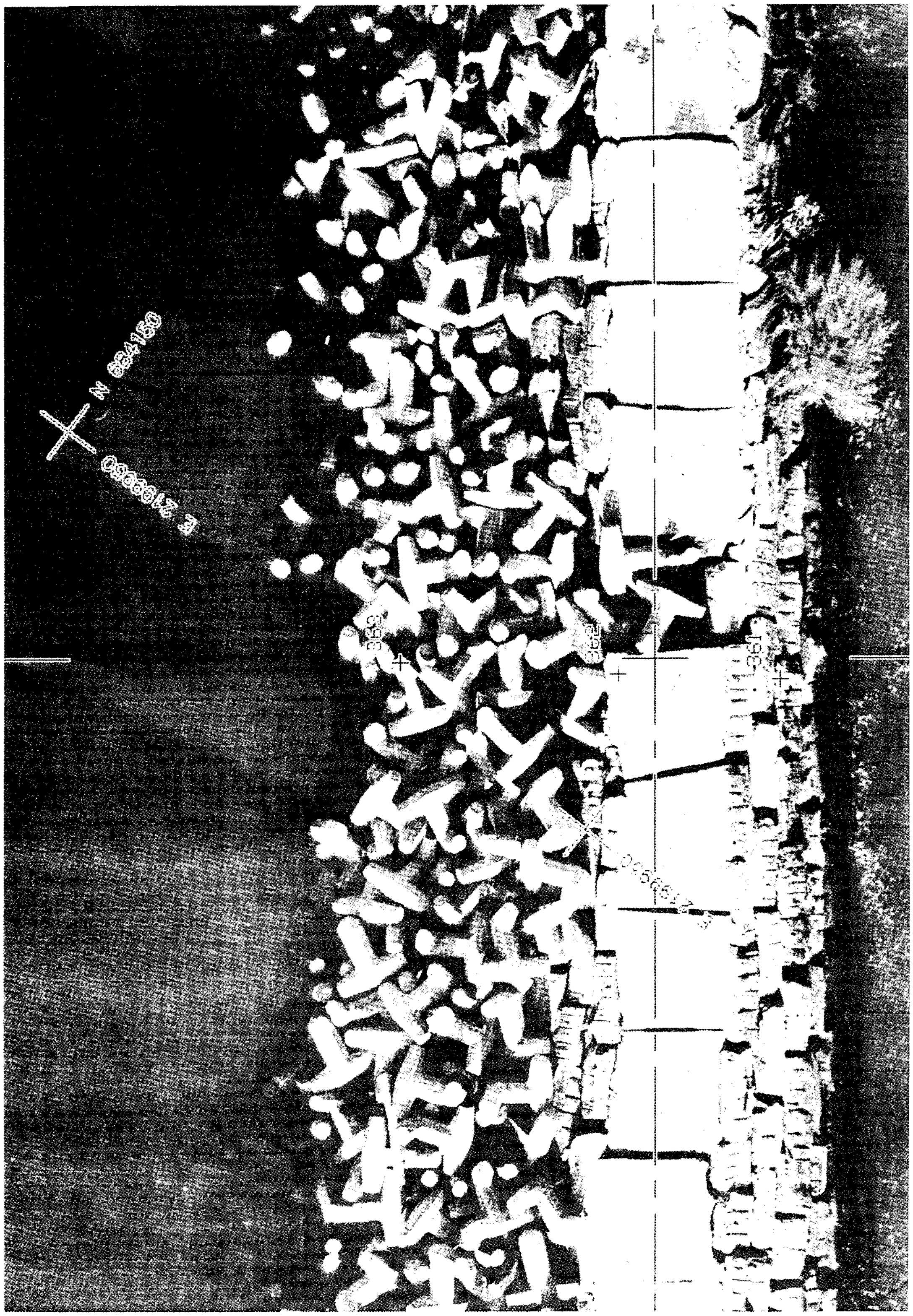


Figure 33. Orthophoto for a portion of the dolos-armored breakwater

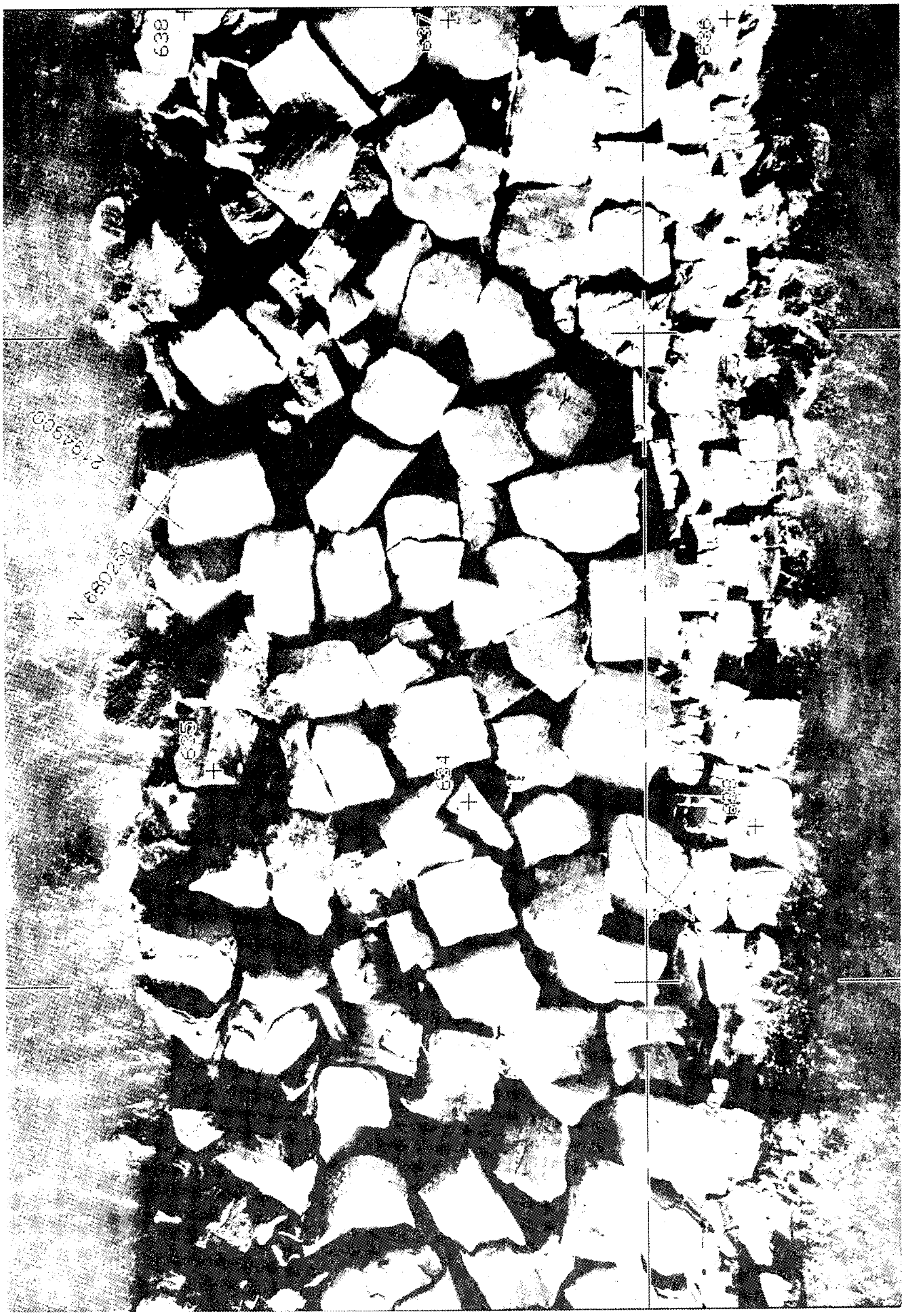


Figure 34. Orthophoto for a portion of the stone-armored breakwater

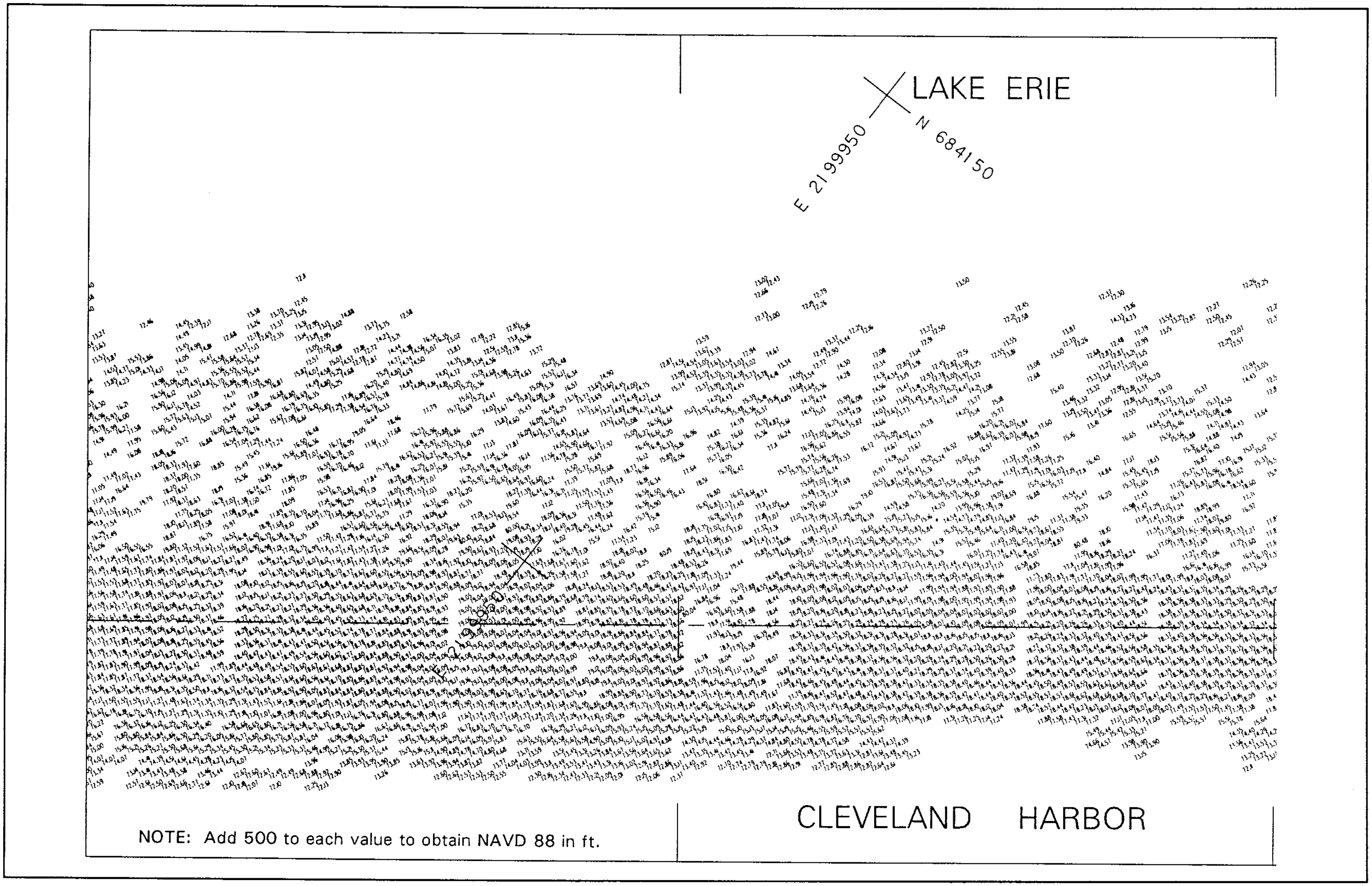


Figure 35. Point plot map of a portion of the dolos-armored breakwater

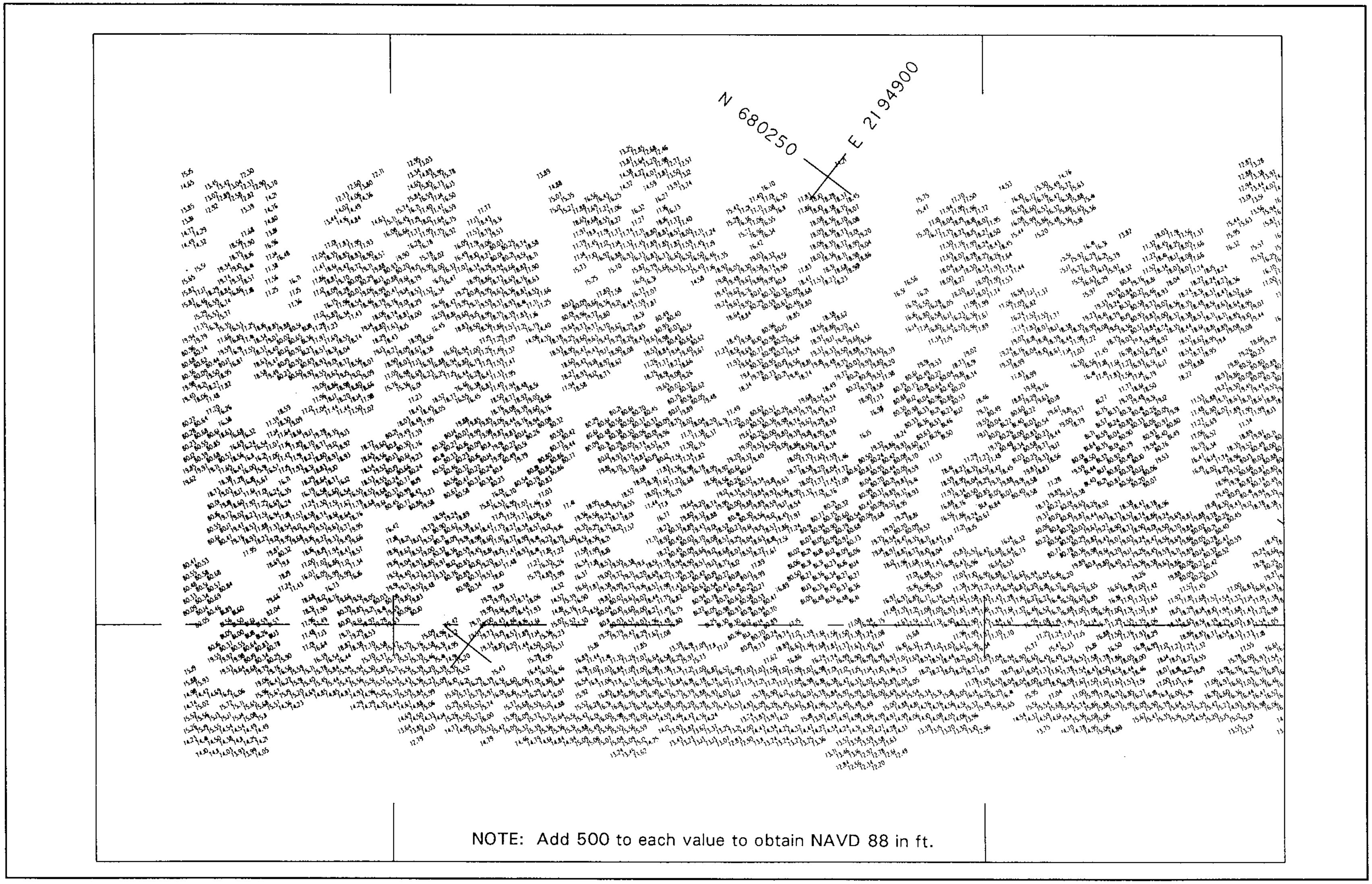


Figure 36. Point plot map of a portion of the stone-armored breakwater

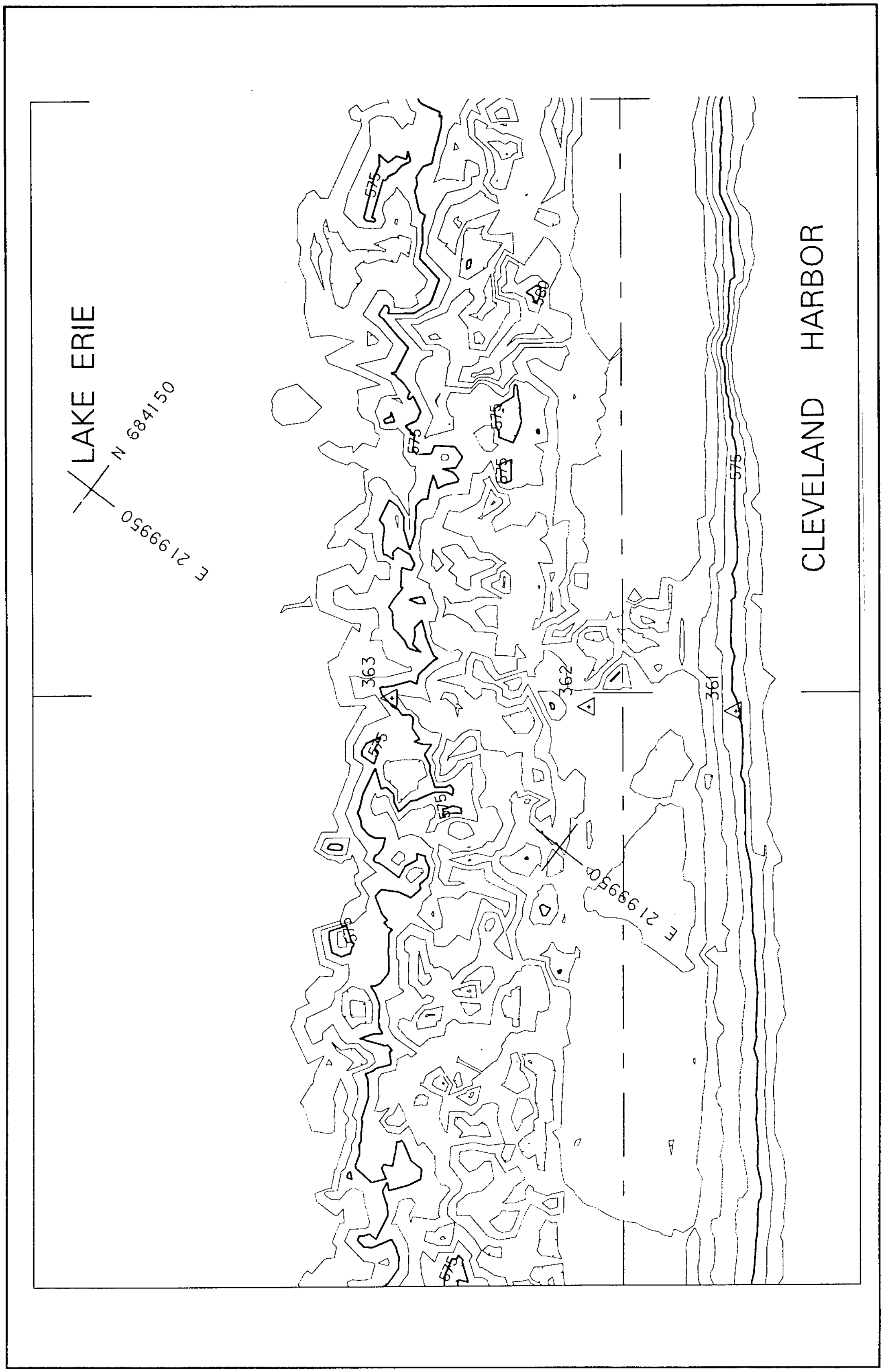


Figure 37. Contour map of a portion of the dolos-armored breakwater

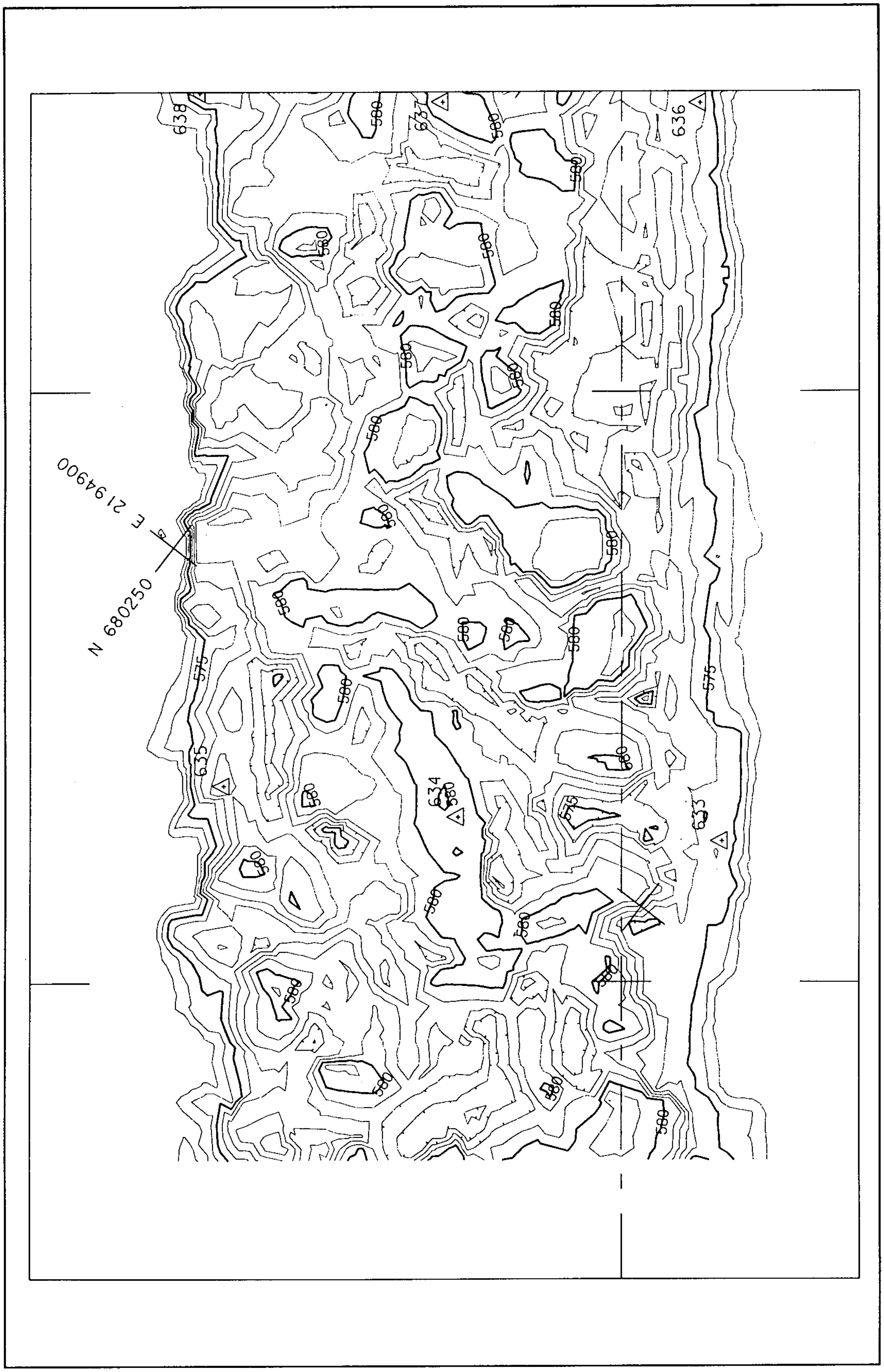


Figure 38. Contour map of a portion of the stone-armored breakwater

dolos armored breakwater and at 18.3-m (60-ft) intervals along the three stone armored portions of the structure monitored. Figures 39 and 40 present computer-generated cross sections of portions of the dolos- and stone-armored breakwater.

Full-scale hardcopies of aerial photos, orthophotos, point plot maps, contour maps, and breakwater cross sections are on file at the authors' offices at CEWES and CENCB. In addition, all digital data, photogrammetric compilations and analysis, image points, and map data have been stored on diskettes in Intergraph files for future use. In summary, very detailed and accurate information relative to the armor unit positions at the Cleveland Harbor East Breakwater have been captured by means of aerial photography and photogrammetric analysis. Digital data, stored on diskettes, can be retrieved and compared against data obtained during subsequent monitoring. Thus, armor unit movement data may be quantified very precisely in future years.

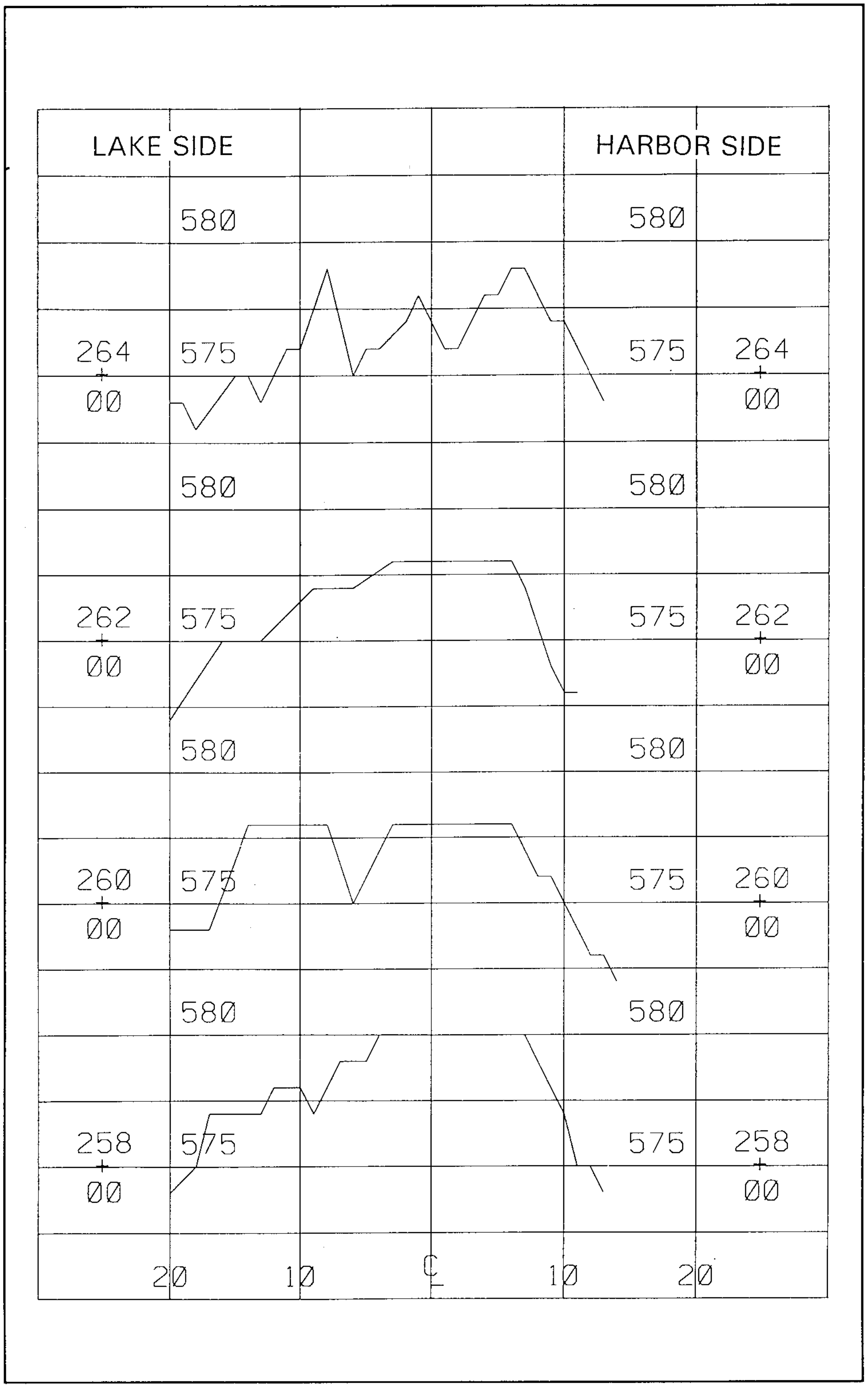


Figure 39. Typical cross sections of portions of the dolos-armored breakwater

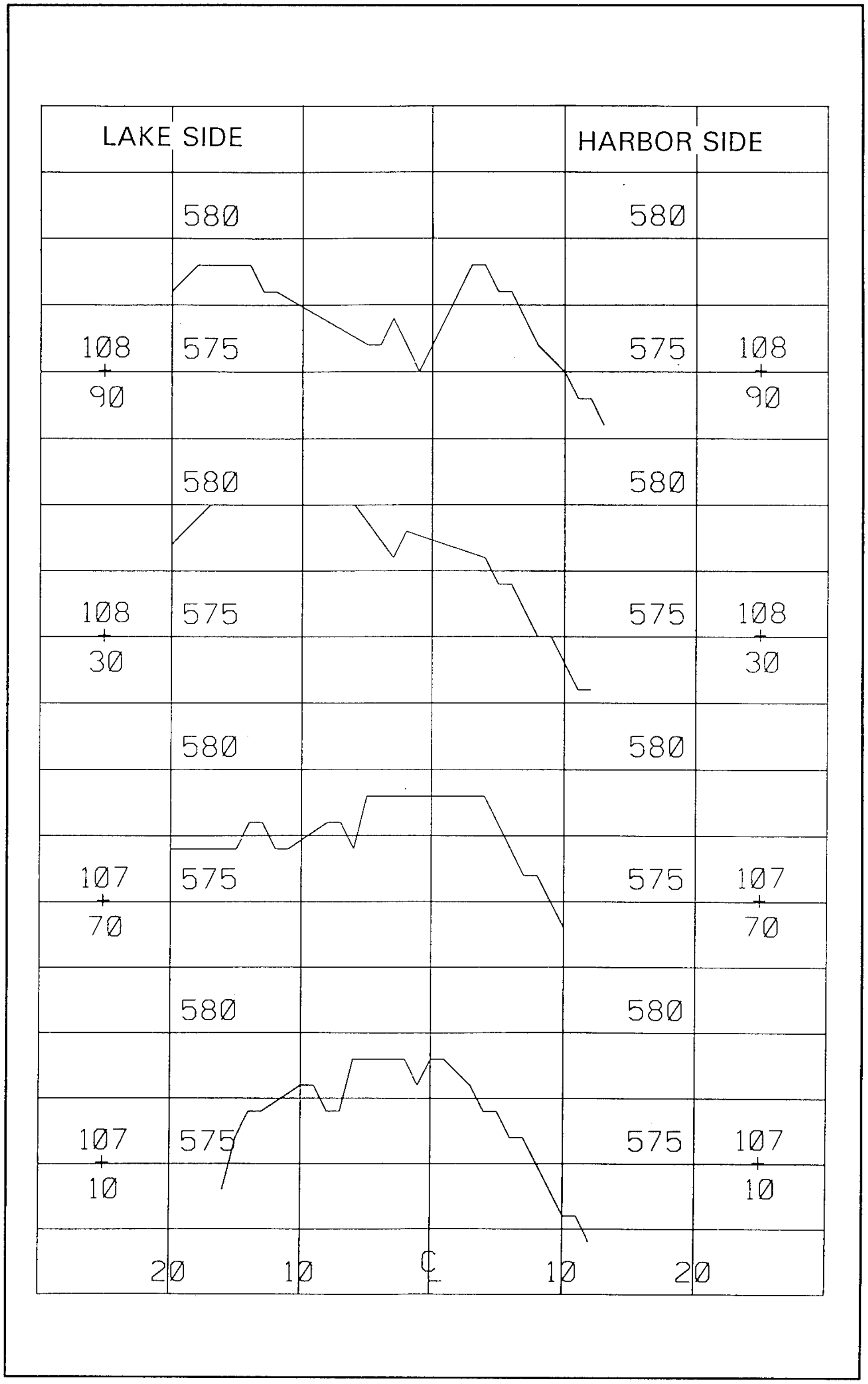


Figure 40. Typical cross sections of portions of the stone-armored breakwater

4 Summary

Originally, data were obtained for the dolos-armored Cleveland Harbor East breakwater during the period 1981-1985 under the Monitoring Completed Coastal Projects Research Program. Armor unit breakage was documented, but limited quantitative data regarding armor unit movement were collected. Many of the units targeted during the effort were lost during storm wave conditions. Several stone rehabilitations of the East Breakwater were completed during the period 1985-1992. Walking inspections indicated extensive fracturing of armor stone. Progression of the stone breakage was documented periodically; however, armor unit movement data are nonexistent.

By means of limited ground-based surveys, low-level aerial photography, and photogrammetric analysis, very precise base level conditions have been established for portions of the Cleveland Harbor East Breakwater under the current Periodic Inspections work unit of the Monitoring Completed Coastal Projects Research Program. Accuracy of the photogrammetric analysis techniques were validated and defined through comparison of ground and aerial survey data on monuments and targeted armor units. A method using high resolution, stereo pair aerial photos, a stereoplotter, and Intergraph based software has been developed to analyze the entire above-water armor unit fields and quantify armor unit movement. Detailed broken armor unit walking surveys conducted during the current effort have resulted in a well-documented data set that was compared with previous survey data.

Now that base (control) conditions have been defined at a point in time and a method has been developed to closely compare subsequent years of high resolution data for the Cleveland Harbor East Breakwater, the site will be revisited during future years under the Periodic Inspections work unit to gather data by which assessments can be made on the long-term response of the structure to its environment. The insight gathered from these efforts will allow engineering decisions to be made, based on sound data, as to whether or not closer surveillance and/or repair of the structure is required to reduce its chances of failing catastrophically. Also, the periodic inspection methods developed and validated for these breakwaters can be used to gain insight into other Corps' structures.

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13. ABSTRACT *(Maximum 200 words)*

Under the Periodic Inspections work unit of the Monitoring Completed Coastal Projects Program, base level conditions have been established for above-water armor units on portions of the Cleveland Harbor East Breakwater. The vertical and horizontal positions of dolos and stone armor units over a cumulative 1,506 m (4,940 ft) of the breakwater have been defined through limited ground surveys, low-altitude aerial photography, and photogrammetric analysis. A database of broken dolos and stone armor units also has been established. The site will be revisited periodically in the future and the long-term structural response of the breakwater to its environment will be tracked. These periodic data sets are used to improve knowledge in design, construction, and maintenance of the existing structure as well as proposed future coastal projects.

14. SUBJECT TERMS

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